Searching for Dark Matter and Dark Energy at CAST and beyond

G. Cantatore (Univ. and INFN Trieste, CERN)

CAST Collaboration

aKWISP working group:
V. Anastassopoulos (Univ. of Patras)
G. Cantatore (Univ. and INFN Trieste, CERN)
S. Cetin (Bilgi Univ.)
H. Fischer (Univ. of Freiburg)
W. Funk (CERN)
A. Gardikiotis (Univ. of Patras)
D.H.H. Hoffmann (TU Darmstadt)
M. Karuza (Univ. of Rijeka and INFN Trieste)
Y.K. Semertzidis (CAPP, Korea)
D. Vitali (Univ. of Camerino)
K. Zioutas (CERN and Univ. of Patras)
S. Zippilli (Univ. of Camerino)

Summary

I. **CAST** at CERN: hunting for Dark Matter and Dark Energy

- current status
- 2016-2018 physics program
- **KWISP**
  - the force sensor and its key technologies
  - recent developments

II. Beyond: the ***a*KWISP** project

- the device
- physics potential

CAST: axions and more

CAST at CERN

- 21 institutes, 48 authors, 12 countries…
- **Probing the mysteries of the Universe since 2003 !!!**

http://cast.web.cern.ch/CAST/CAST.php

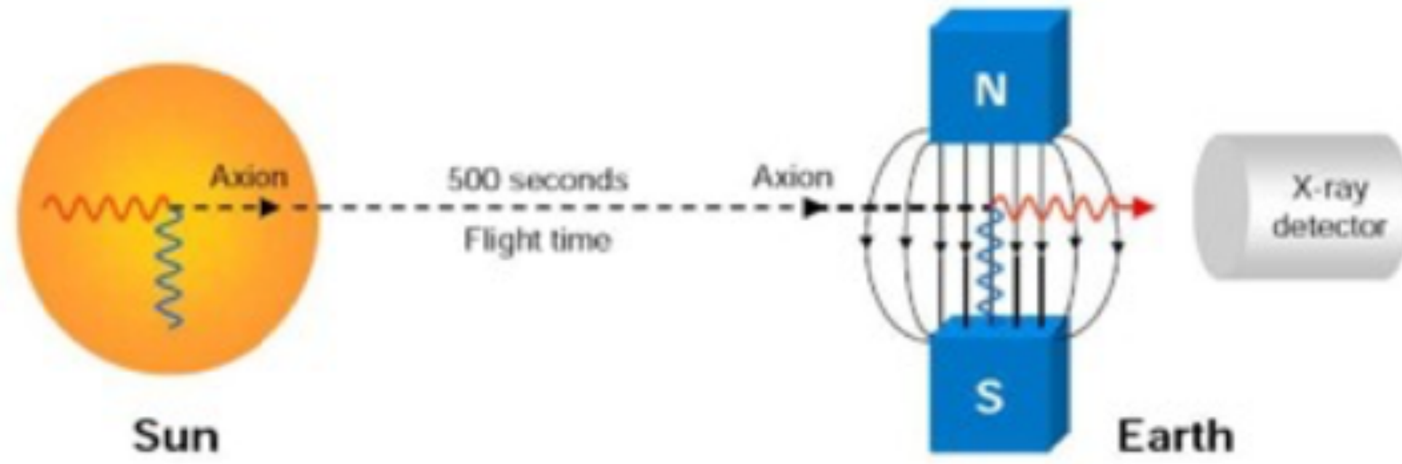
The CAST physics program

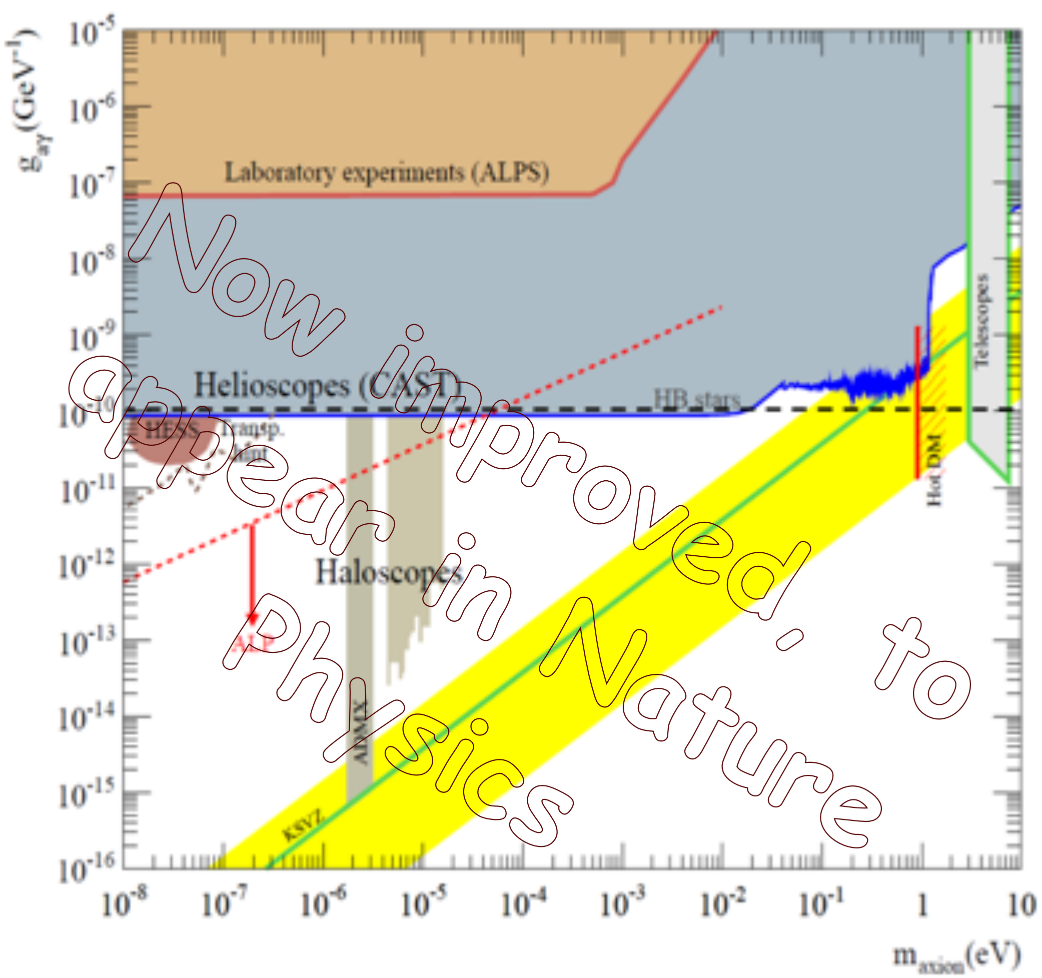
- CAST has terminated its solar axion search program at the end of 2015
  - analysis of the latest vacuum data is now complete, will appear shortly in Nature Physics. **CAST is still the benchmark reference for axion searches**
- A **new 2016-2018 physics program** for CAST has been approved by CERN (*) in October 2015
- CAST expands its horizons to Dark Matter and Dark Energy with three new research lines
  - relic axion searches with CAPP@CAST and RADES
  - solar Chameleon searches with InGrid (two-photon coupling)
  - solar Chameleon searches with KWISP (direct coupling to matter)

(*) see G. Cantatore, L. Miceli, K. Zioutas, "Search for solar chameleons and relic axions with CAST", CERN-SPSC-2015-021

CAST solar axion program

2003-2015: Solar axions





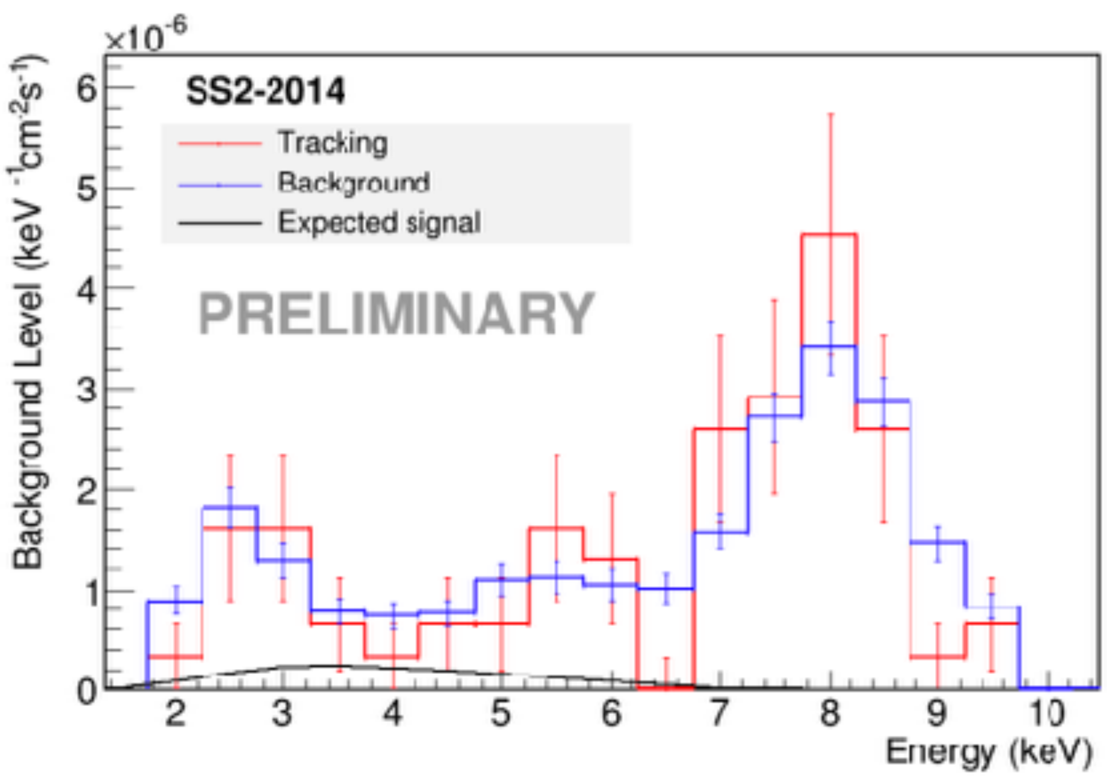
- world-best limit on solar axions
- exclusion of QCD axion at high m
- strongest non-astrophysical exclusion of ALPS in a wide mass range

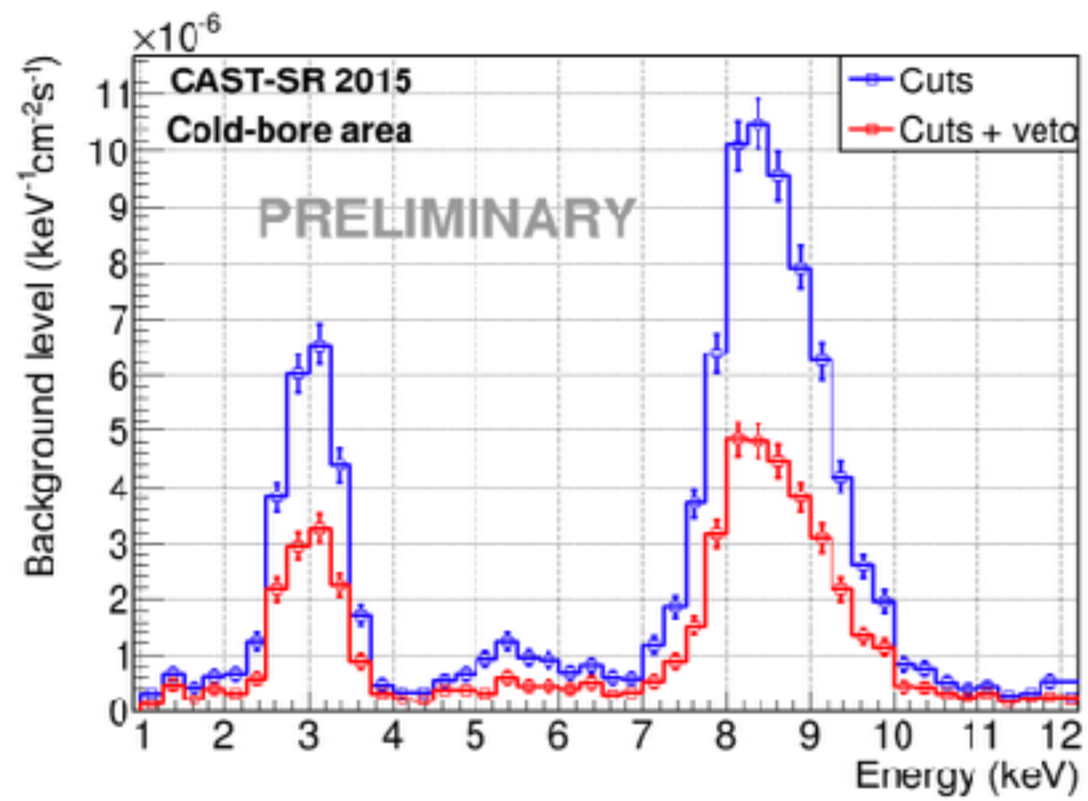
Data analysis: 2013-2015 Micromegas run

- Lowest-ever background levels in three MM detectors (SS1, SS2, SR)
  ~ 10^{-6} /cm²/keV/s

- Large sun exposure (SS ~ 440h, SR ~290h)

- Reduction of integrated BG through new LLNL XRT for SR line)

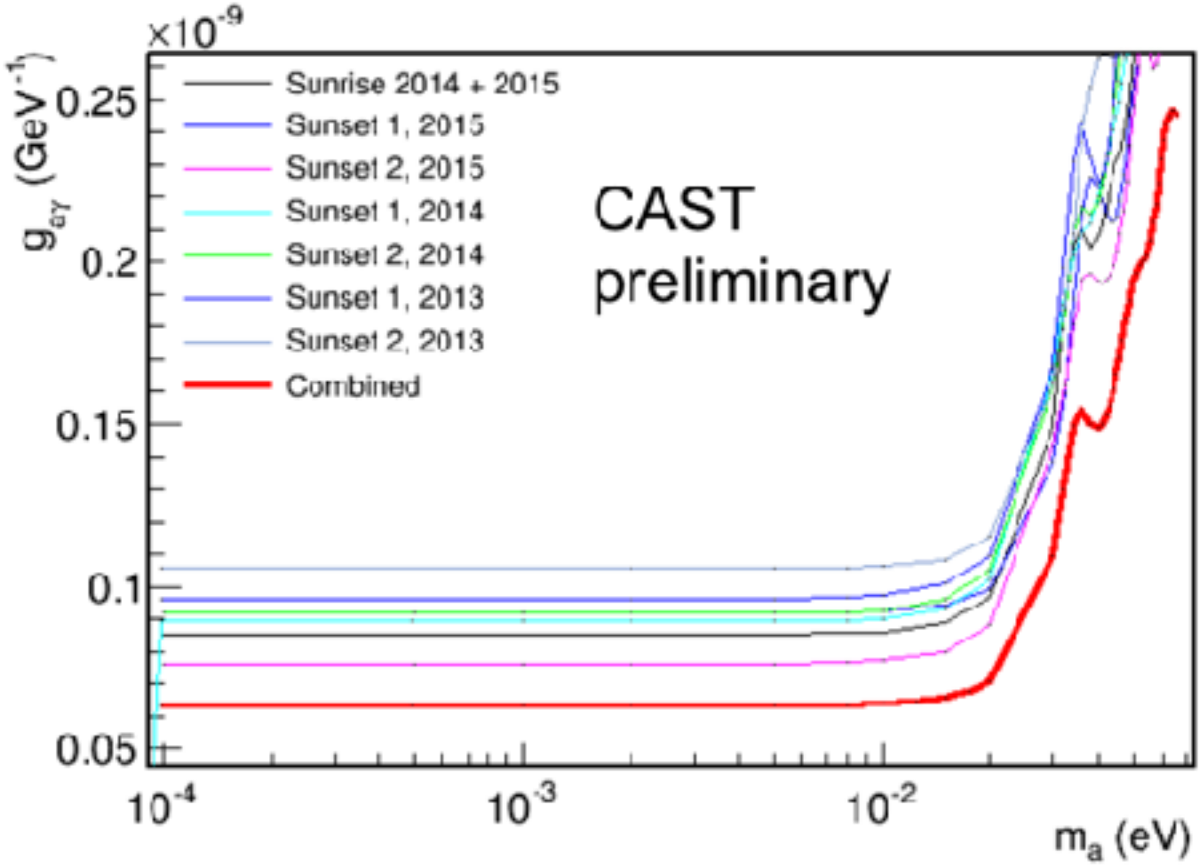




Preliminary result

SR (2014, 70h): 0.2±0.?? background events expected, 0 observed
SR (2015, 220h): 0.6±0.13 background events expected, 3 observed
Energies of the 3 events: 3.05 keV, 2.86 keV, 2.56 keV

Full likelihood analysis all 2013-2015 data → data compatible with BG-only hypothesis



$g_{a\gamma} < 0.63 \times 10^{-10}$
(for m_a < 200 meV)
(preliminary)

Improvement of previous CAST limit ($g_{a\gamma} < 0.88 \times 10^{-10}$)

~ factor ~4 improvement in observable flux!

(again) better than astrophysical limit from stellar cooling entering interesting “hint“ region

2016-2018 Proposal

Four complementary „experiments“:

	Physics	Magnet	XRT	Sun tracking
InGrid	Solar chameleons (X-ray detector)*	✅	✅	✅
KWISP	Solar chameleons (force sensor)	❌	✅	✅
CAST-CAPP	Relic axions (cavitiy)	✅	❌	❌
RADES	Relic axions (cavity)	✅	❌	❌

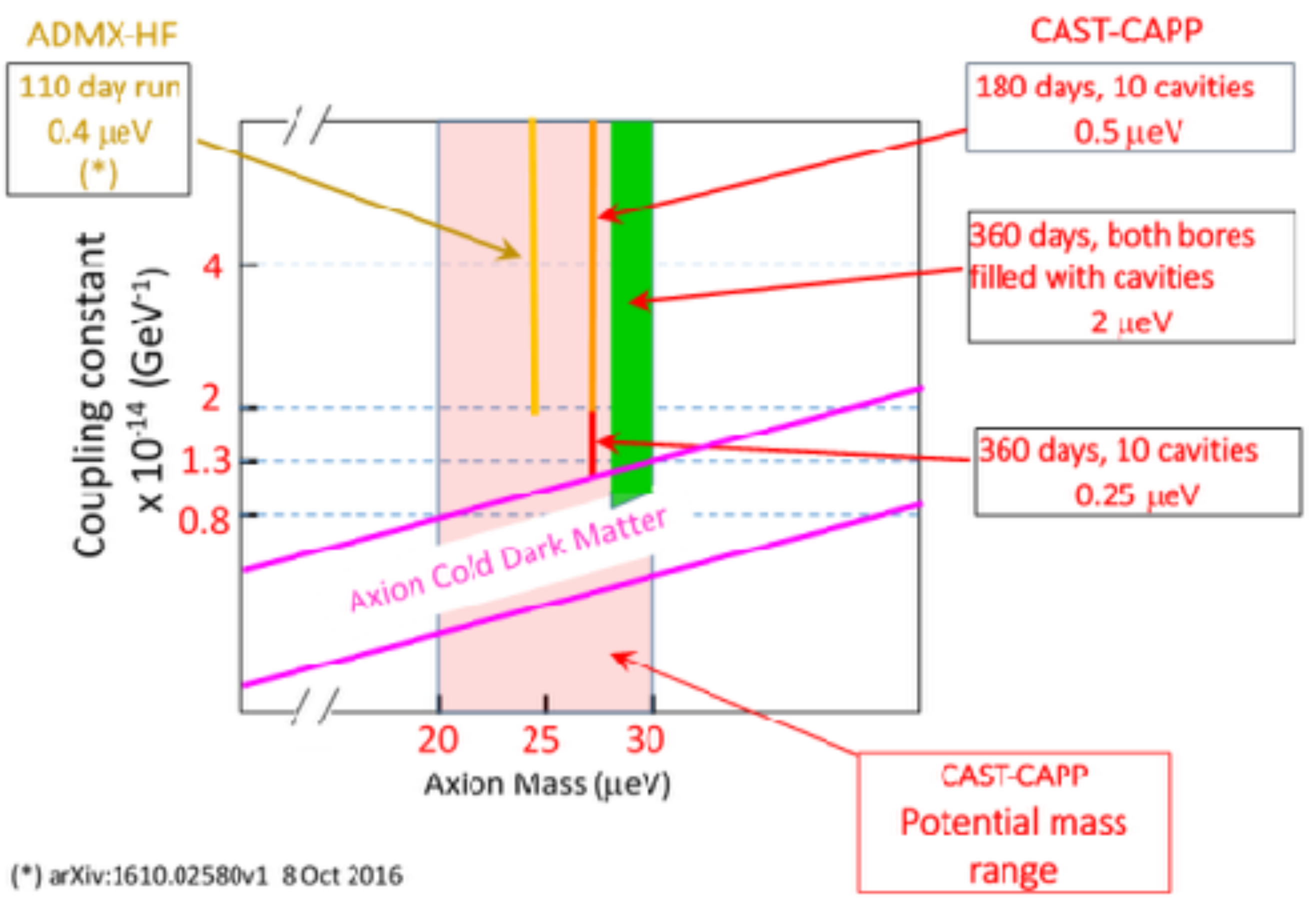
The CAST spirit: make optimal opportunistic use of existing infrastructure
2016: year of commissioning/improving the new experiments

* also sensitive to axions ($g_{a\gamma}$, $g_{ae}\cdot g_{a\gamma}$)

CAST-CAPP

Idea: search for relic axions resonating into microwave photons in a cavity immersed into the CAST magnetic field („haloscope approach“)

Fixed frequency → sensitivity to single axion mass m_a [μeV] ≈ 4.13 ν [GHz]
→ tuning of cavity to scan axion mass
→ increase sensitivity by multiple cavities



(*) arXiv:1610.02580v1 8 Oct 2016

18/10/2016 K. Desch - Status and Plans of CAST

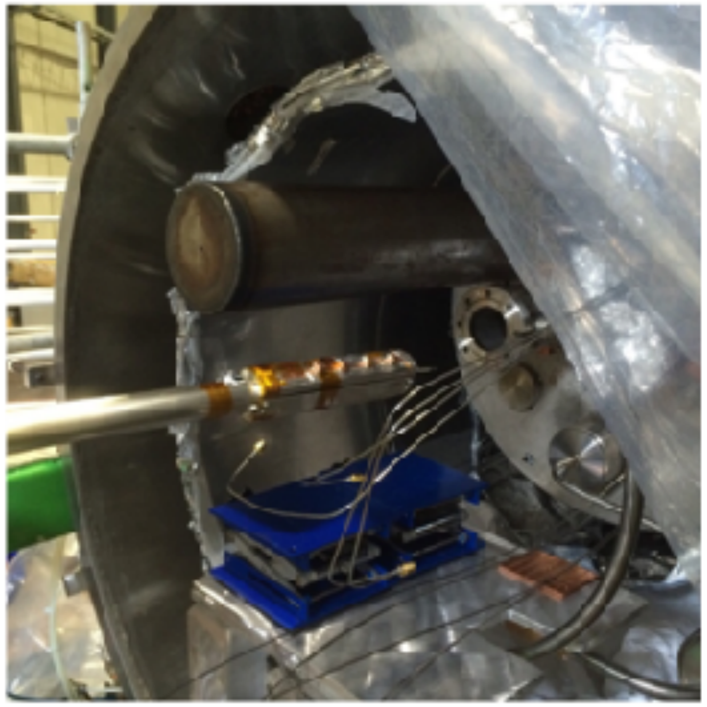
CAST-CAPP – 2016 progress

First cavity installed inside the CAST magnet (V2 bore) on June 20, 2016

Dimensions: 108 mm x 25 mm x 23 mm (ν≈6.05 GHz, not tuneable, Q~10000)

Position: 108 cm from flange, full field region

Cavity

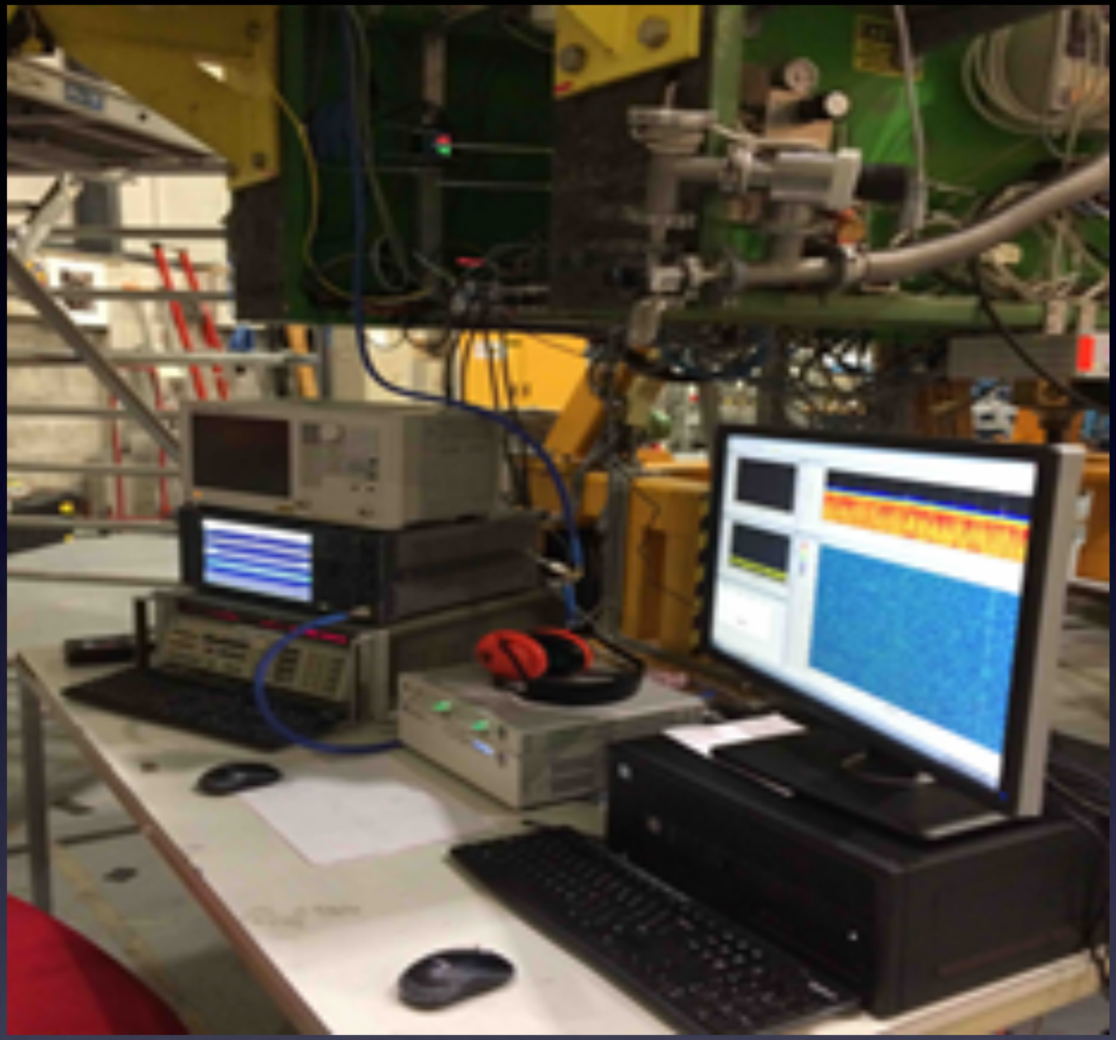


Insertion into magnet bore

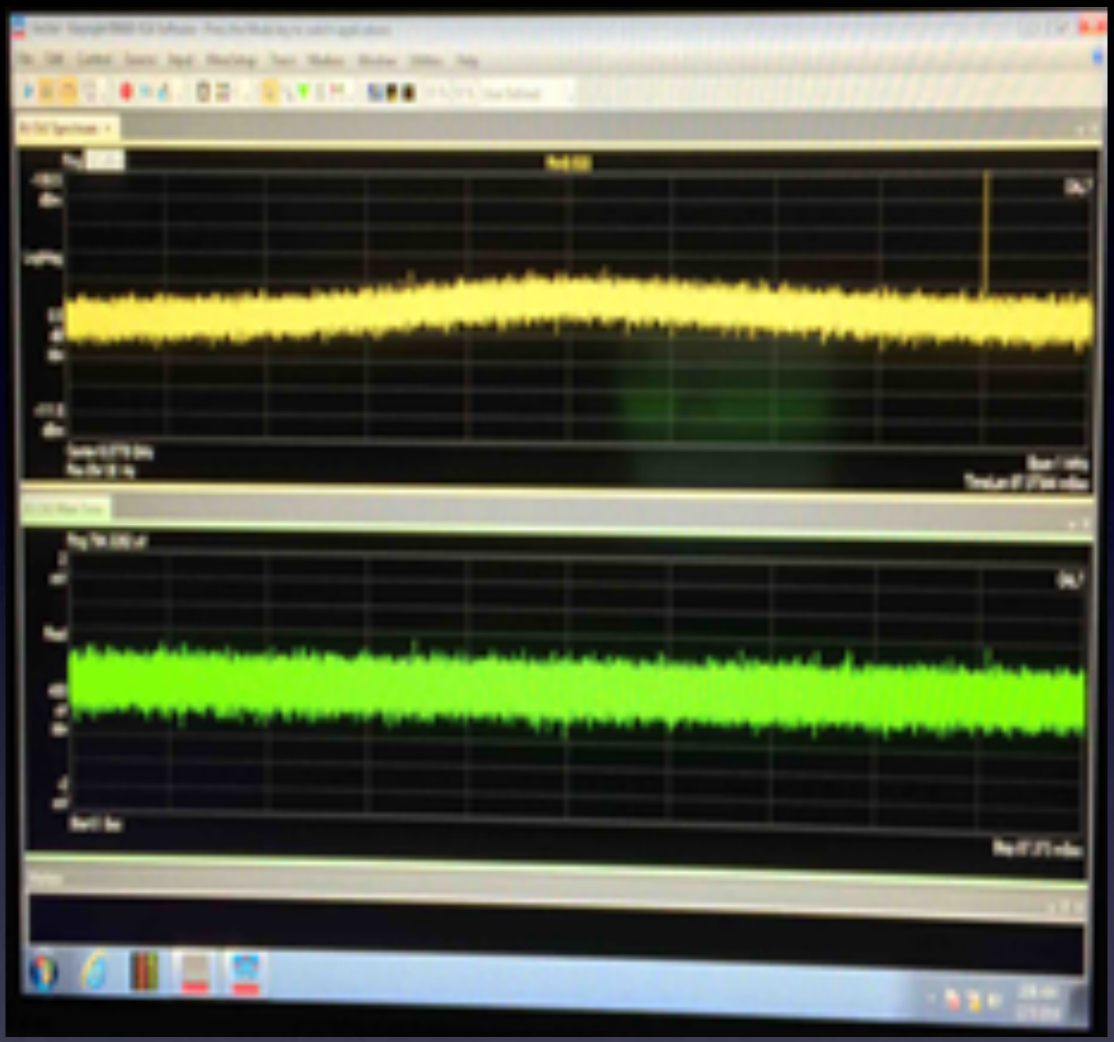
Vacuum vessel connected to the magnet bore

Signal transported to cryogenic low-noise HEMT amplifier inside vacuum vessel, outside cold bore. T measured: 2.4 K

CAPP cavity commissioning at CAST



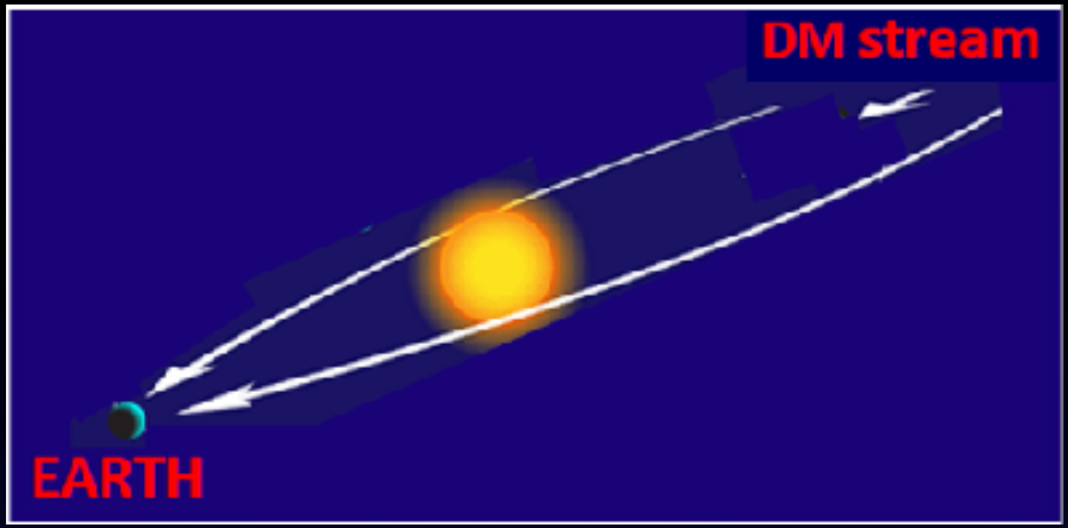
CAPP cavity control setup at CAST (L. Miceli)



Cavity and instrumentation noise spectra (L. Miceli)

- CAPP cavity started data taking at CAST in October 2016

Search for axions in streaming dark matter



(*)

- We propose a new search strategy for DM axions (see arXiv:1703.01436v1)
  - DM axion streams might undergo periodic gravitational lensing and the local density is then temporarily highly enhanced, perhaps up to a factor 10^6 (trapped axion miniclusters may also contribute)
  - a wideband (fast-scanning) axion haloscope can be kept online for long periods to detect such events
    - sacrifice baseline sensitivity for scanning speed
    - compensate with the enhanced flux
  - **CAPP is preparing to implement this strategy at CAST**

(*) Picture taken from CERN EP Newsletter 17/3/2017, https://ep-news.web.cern.ch/content/search-axions-streaming-dark-matter

Solar Chameleon production

- Chameleons are a type of scalar WISPs have an effective mass depending on the local matter density
- This makes them candidate constituents for the Dark Energy and allows evading constraints on short range interactions fixed by "fifth-force" measurements.
- Chameleons couple
  - to two photons (Primakoff effect inside a magnetic field)
  - directly to matter (no magnetic field needed)
- To estimate the spectrum of the Chameleon flux emitted by the sun one can assume that production takes place in the solar tachocline region, with a 30 T magnetic field inside it, then linearly decreasing outside.
- In short:
  - Chameleons are produced in the solar magnetic field from the conversion of photons (coupling β_γ)
  - they propagate unhindered to Earth
  - under specific conditions Chameleons interact directly with matter (coupling β_m), in particular by reflecting off a suitable surface

matter coupling

photon coupling

$$V_{\text{eff}}(\phi) = \frac{\Lambda^{4+n}}{\phi^n} + e^{\frac{\beta_m}{M_{\text{Pl}}}\phi}\rho_m + e^{\frac{\beta_\gamma}{M_{\text{Pl}}}\phi}\rho_\gamma,$$

Effective potential

matter coupling

local matter density

$$m^2_{\text{eff}} = (n+1)\frac{\beta_m \rho_m}{M_{\text{Pl}}}\frac{1}{\phi_{\text{min}}}.$$

Effective mass

solar magnetic field

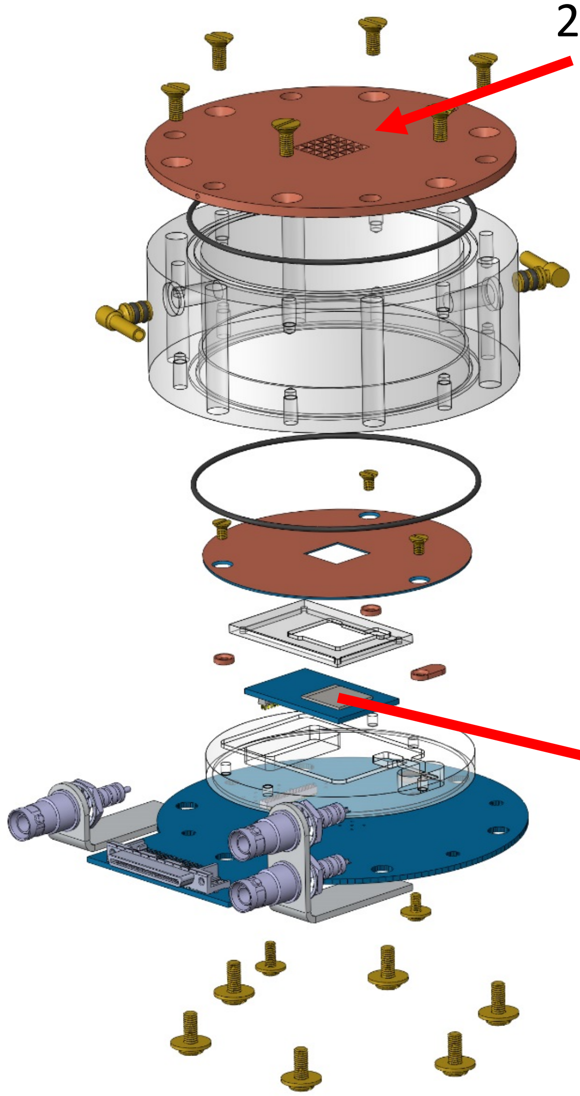
photon coupling

$$P_{\text{chameleon}}(\omega) = 2\theta^2 = 2\left(\frac{\omega B \beta_\gamma}{M_{\text{Pl}}\left(m^2_{\text{eff}} - \omega^2_{\text{pl}}\right)}\right)^2.$$

Photon-chameleon conversion probability assuming production in the solar tachocline

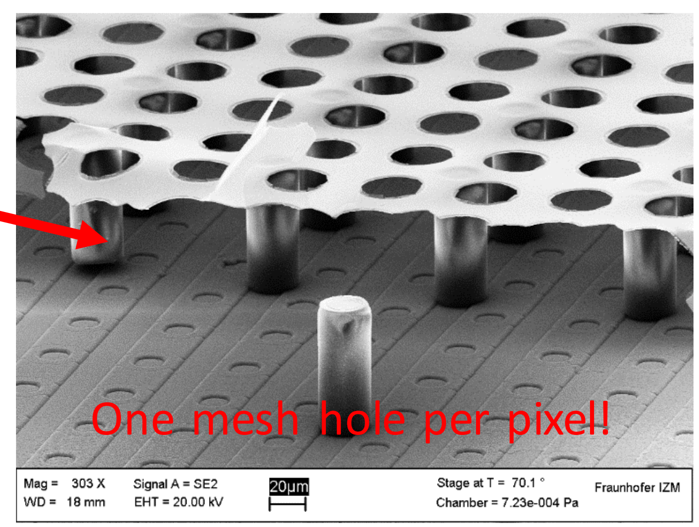
The InGrid based X-ray detector

2 μm Mylar entrance window

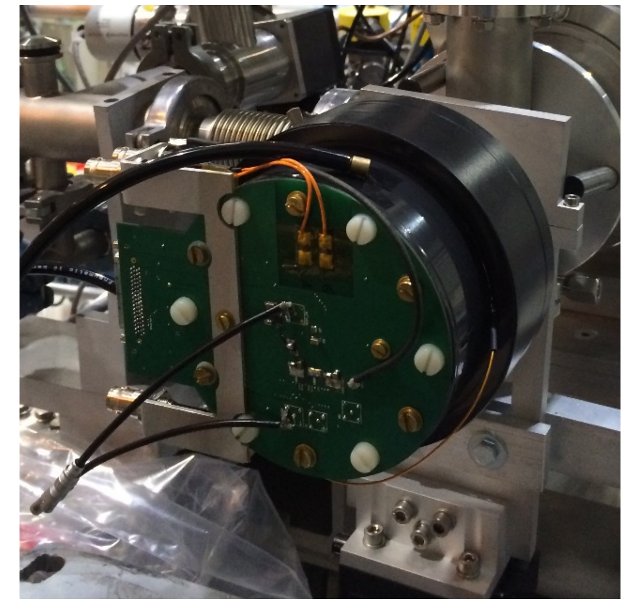


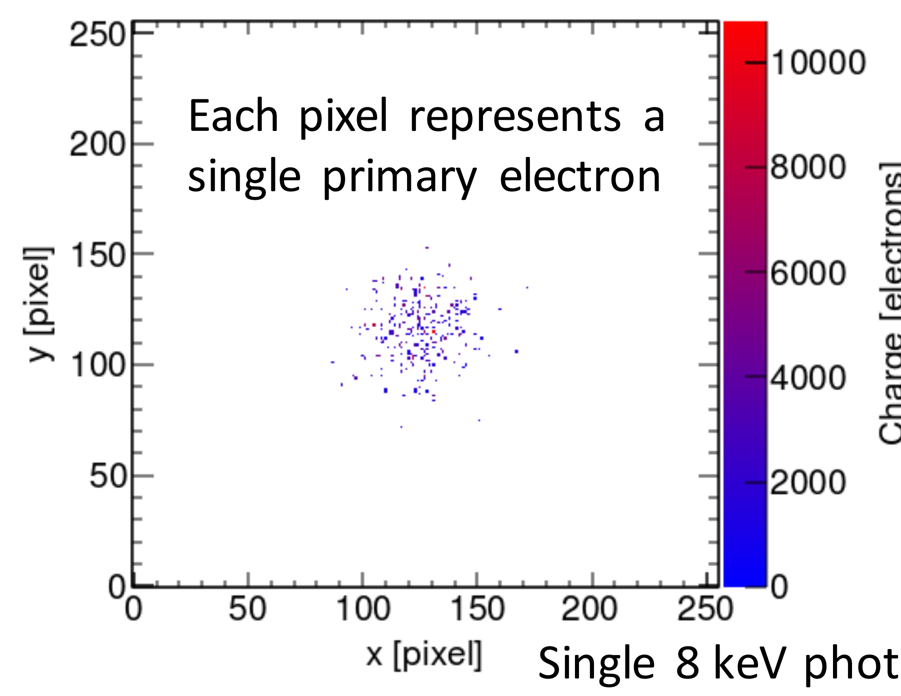
Detection of photons down to 277 eV (Carbon K_{α} line) possible

Timepix ASIC combined with integrated Micromegas stage (InGrid)



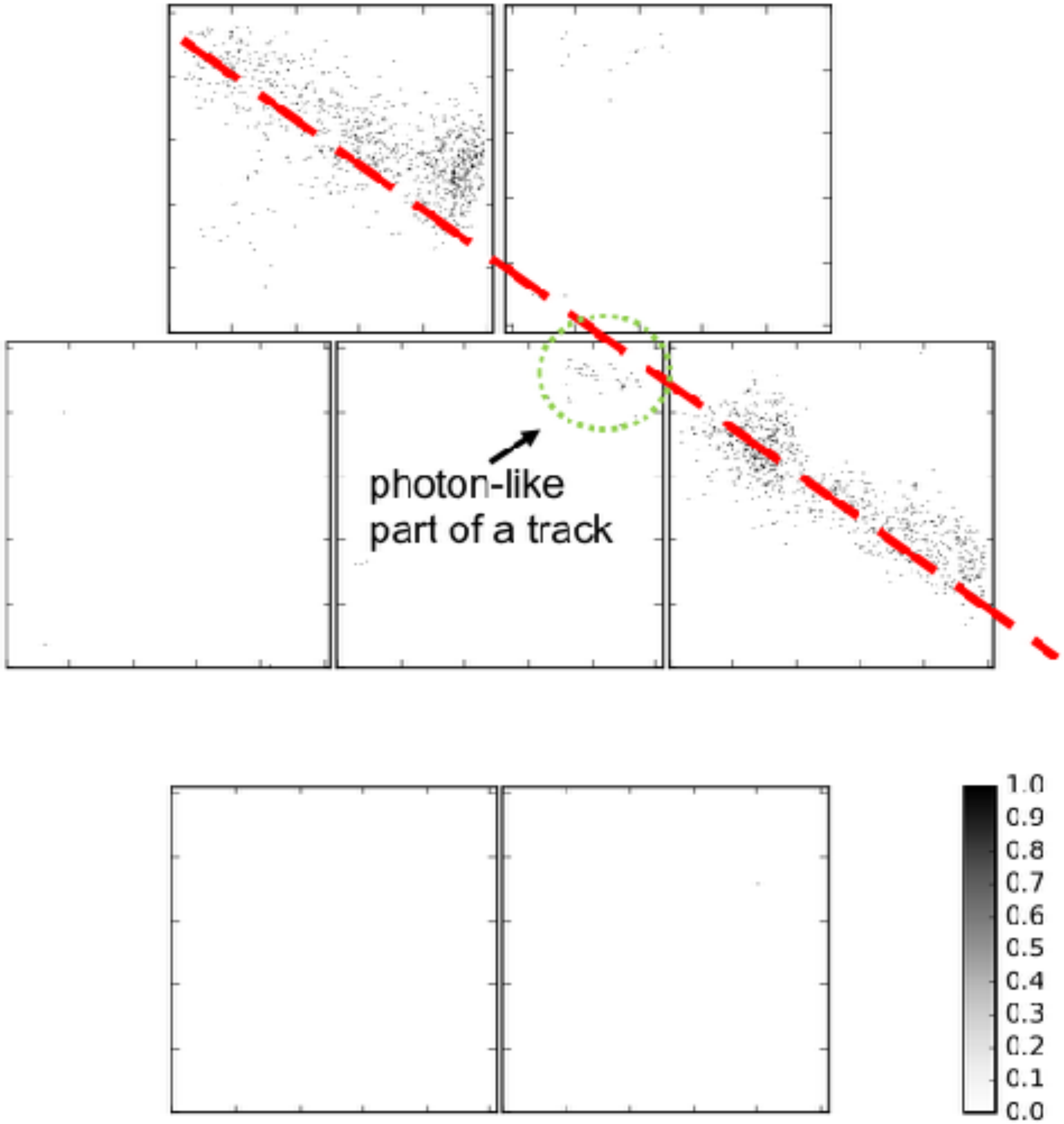
InGrid based X-ray detector





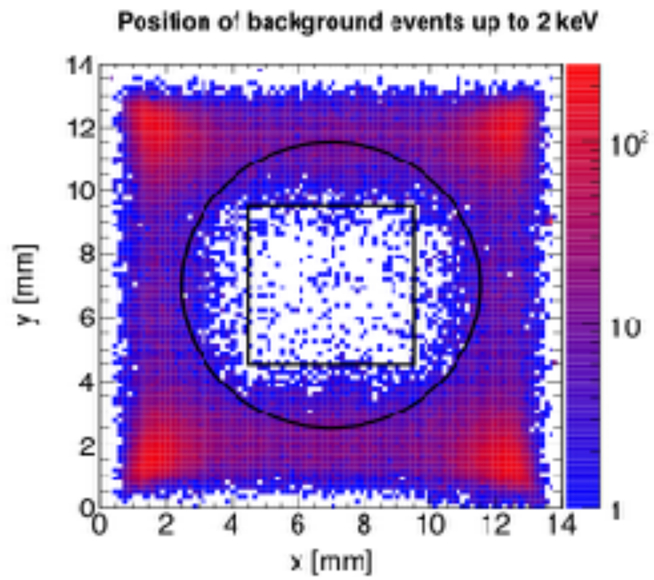
Single 8 keV photon

7 InGrids at work



photon-like signature on central InGrid can now be easily vetoed by the surrounding chips

→ should reduce remaining background significantly



Background distribution on single InGrid chip in 2015

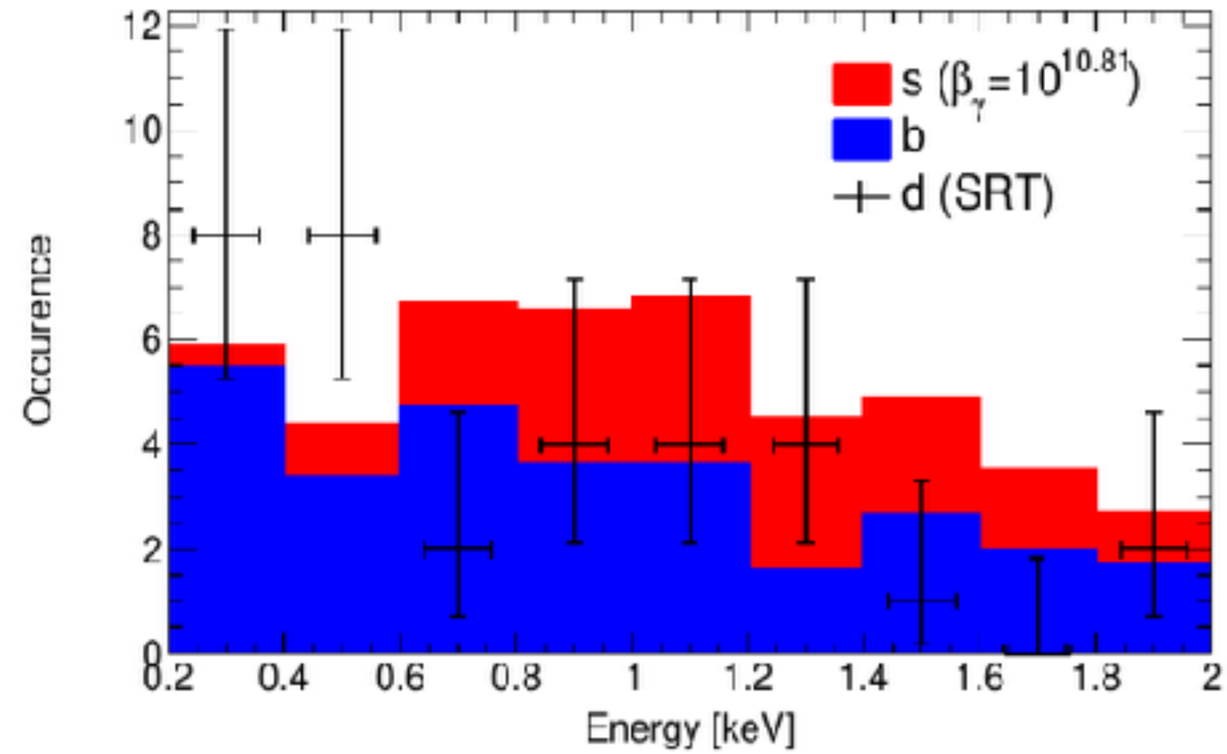
Status solar chameleon search (InGrid)

Observed events in „chameleon" region consistent with background hypothesis
Preliminary (expected) limit on solar chameleons:

$\beta_\gamma < 6.2 \times 10^{+10}$
preliminary, expected 95% C.L., for "benchmark" chamelon parameters, see CAST SDD paper

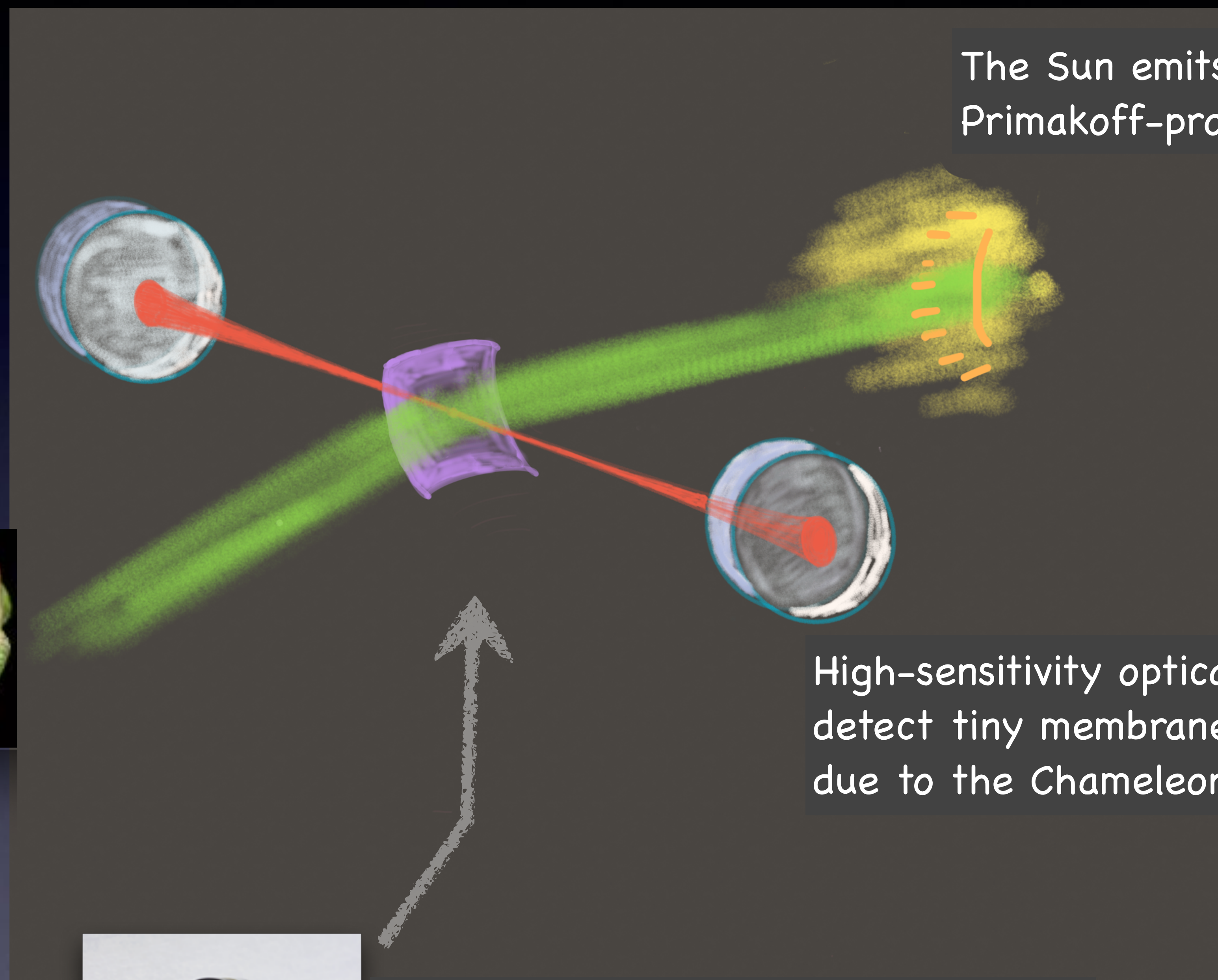
→ stronger than limit from sun cooling ($6.46 \times 10^{+10}$)

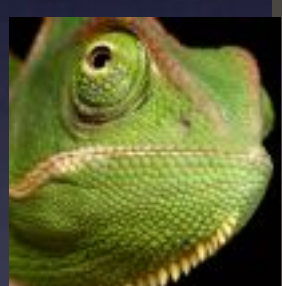
Some open issues:
- XRT parameters at low energies to be clarified
- Fix solar chameleon angular distribution (theory...)



The KWISP principle

The Sun emits a stream of Primakoff-produced Chameleons





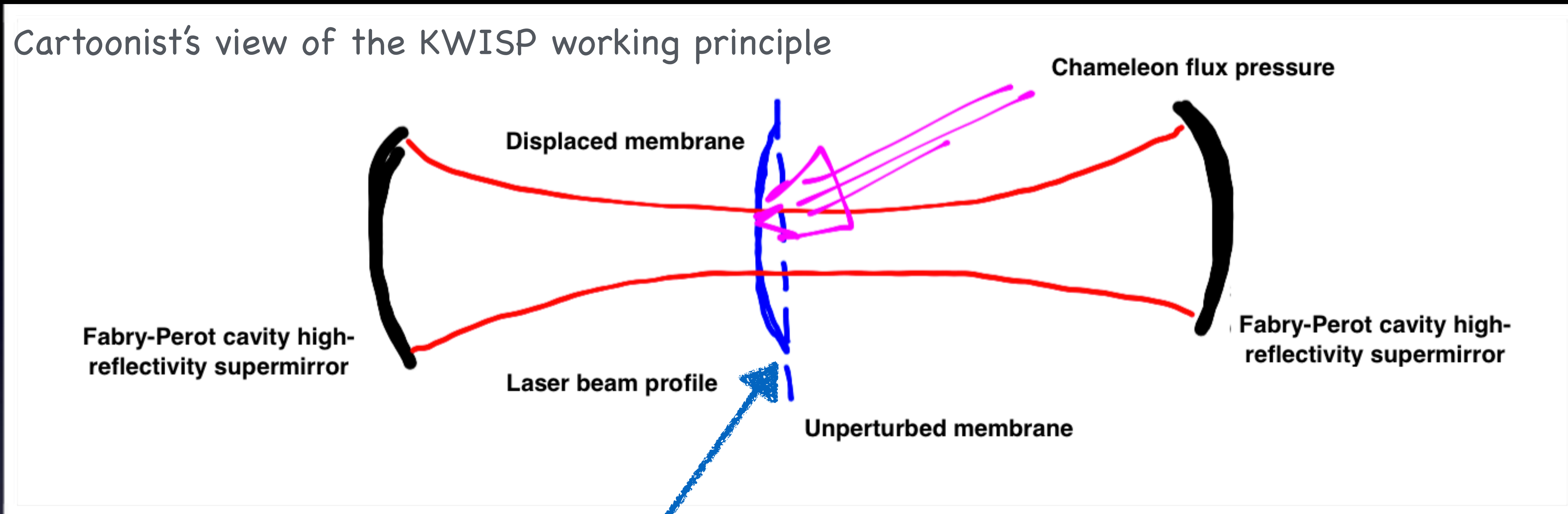
High-sensitivity optical techniques detect tiny membrane displacements due to the Chameleon wind force

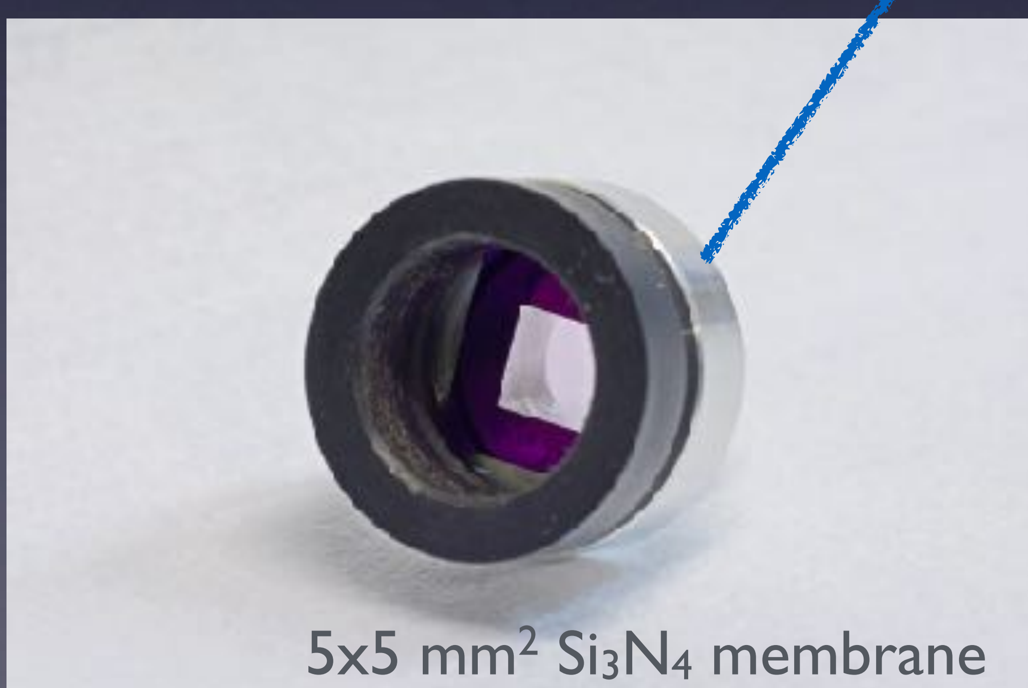
An ultra-thin taut membrane flexes as a sail under the Chameleon wind

Curious? See January-February 2016 CERN Courier http://cerncourier.com/cws/article/cern/63705

Flash introduction to the KWISP force sensor

KWISP @ CAST

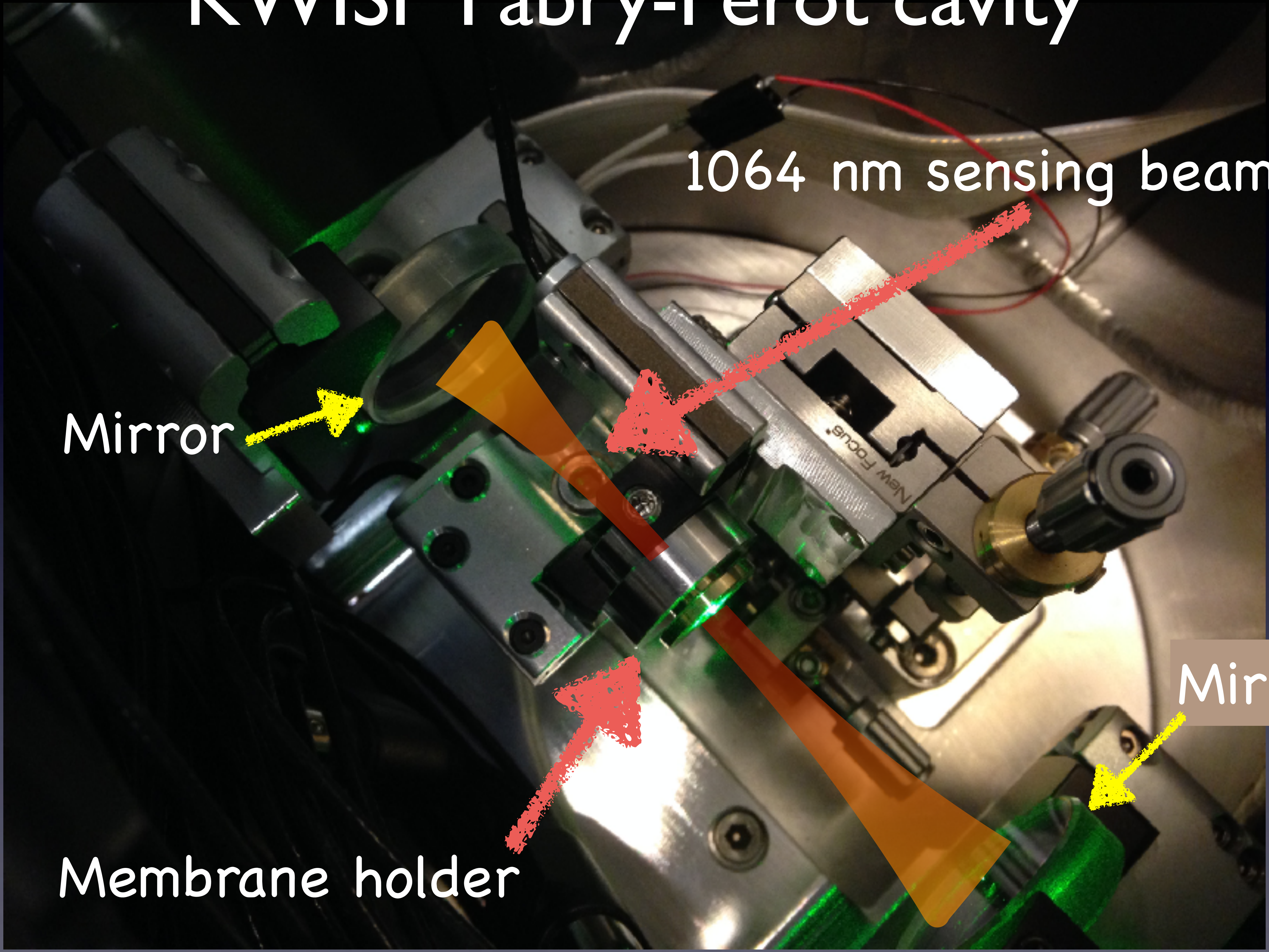



5x5 mm^2 Si_3N_4 membrane

- The opto-mechanical sensor technology is already in use at CERN
- The CAST experiment is equipped with the KWISP detector looking for the direct coupling to matter of solar Chameleons

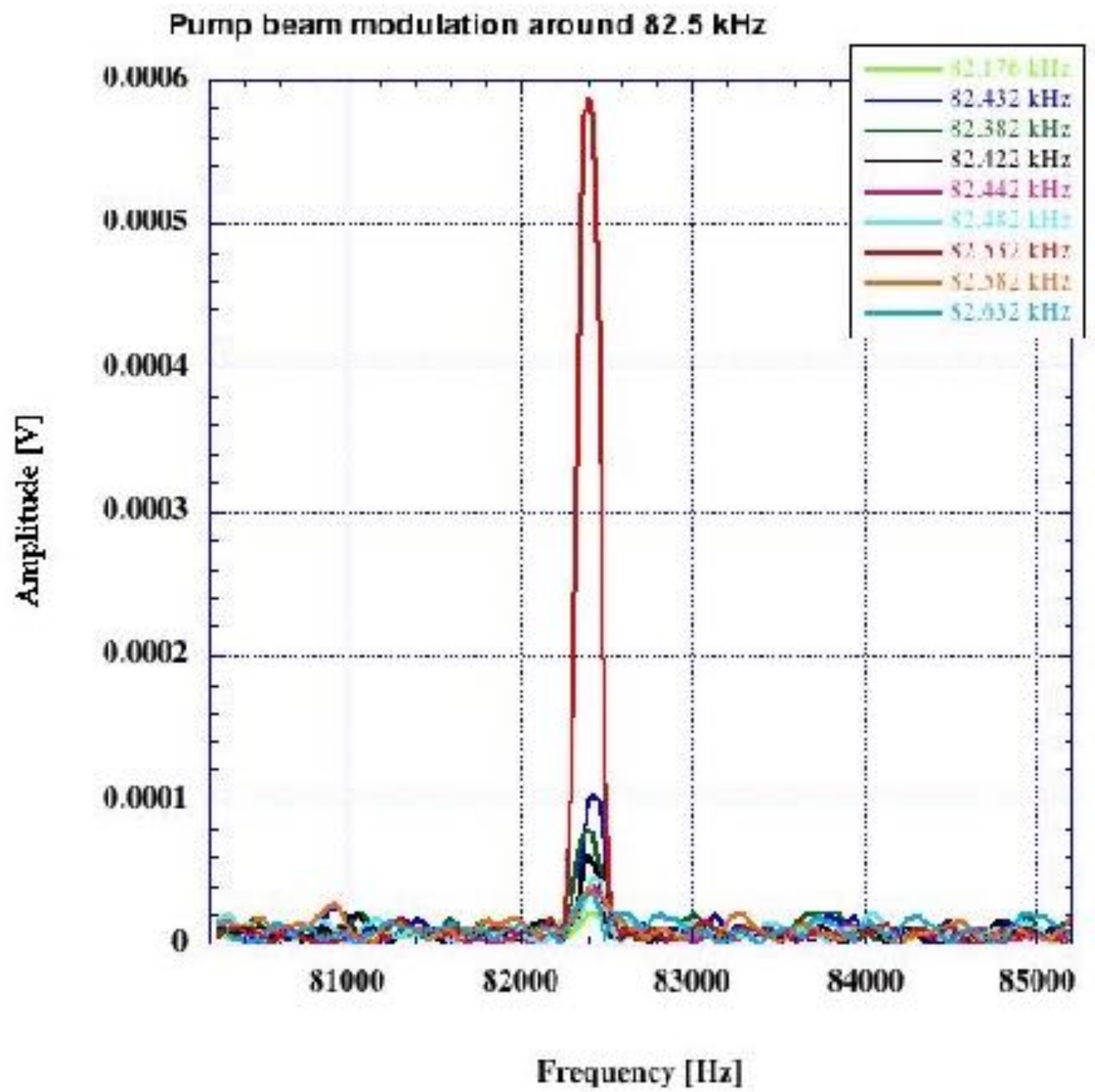
(see G. Cantatore, M. Karuza and K. Zioutas, Cern Courier, January-February 2016)

KWISP Fabry-Perot cavity



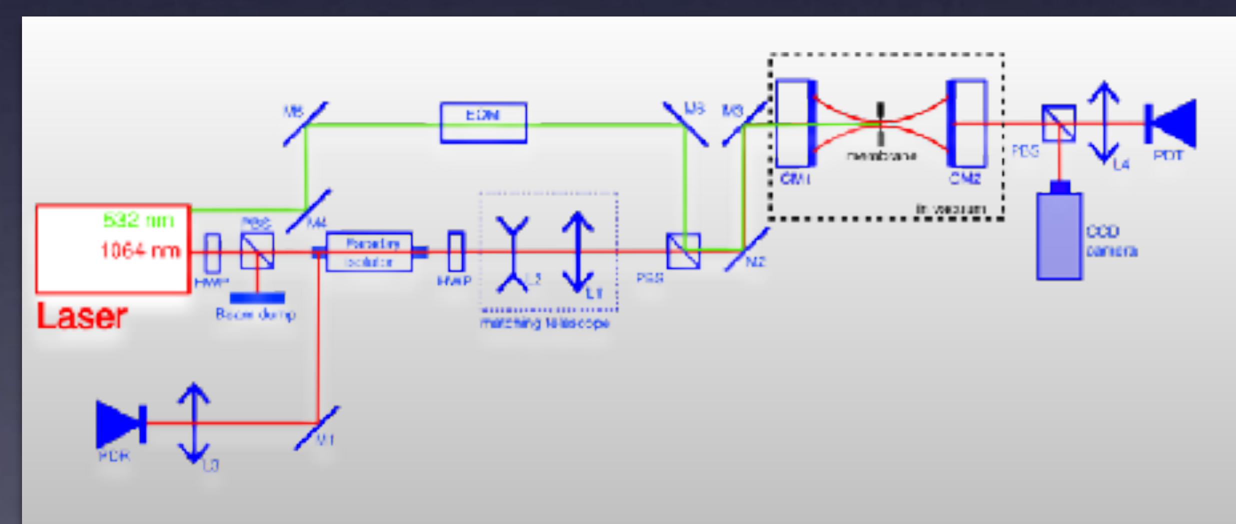
Direct force calibration of the KWISP sensor

Equivalent force on membrane: $7.9 \cdot 10^{-14}$ N



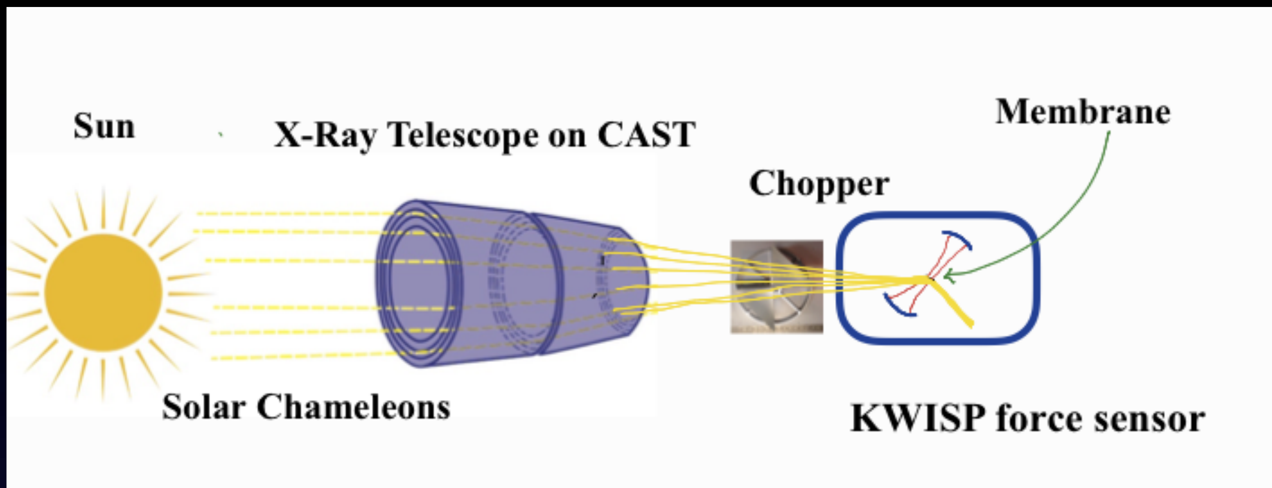
T = 300 K

- A known radiation pressure from a "pump" beam at 532 nm (membrane reflects 25%) is amplitude modulated at the membrane mechanical resonance frequency (82.5 kHz in this case)
- The amplitude of the membrane displacement in response to the force is amplified by a factor Q (3000, up to 10^5)
- **Room temperature sensitivity at resonance: $1.7 \cdot 10^{-17}$ N/$\sqrt{\text{Hz}}$**
- **measurements carried out in the Trieste INFN lab** (see M. Karuza, G. Cantatore, A. Gardikiotis, D.H.H. Hoffmann, Y.K. Semertzidis, K. Zioutas, Physics of the Dark Universe, 12 (2016) 100-104)



This procedure is fully equivalent to calibrating a particle detector with a radioactive source

KWISP at CAST

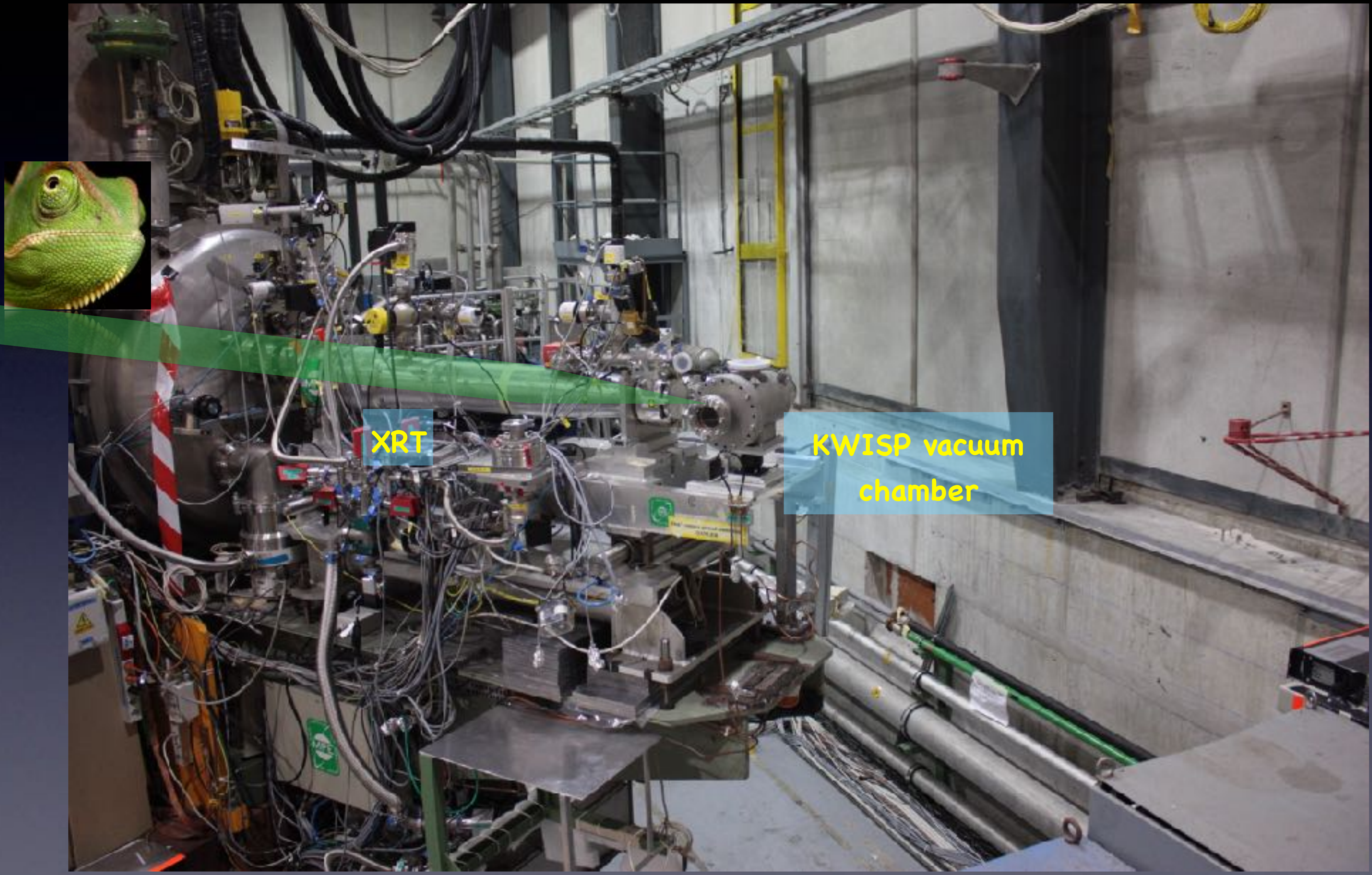


X-ray telescope

KWISP chamber

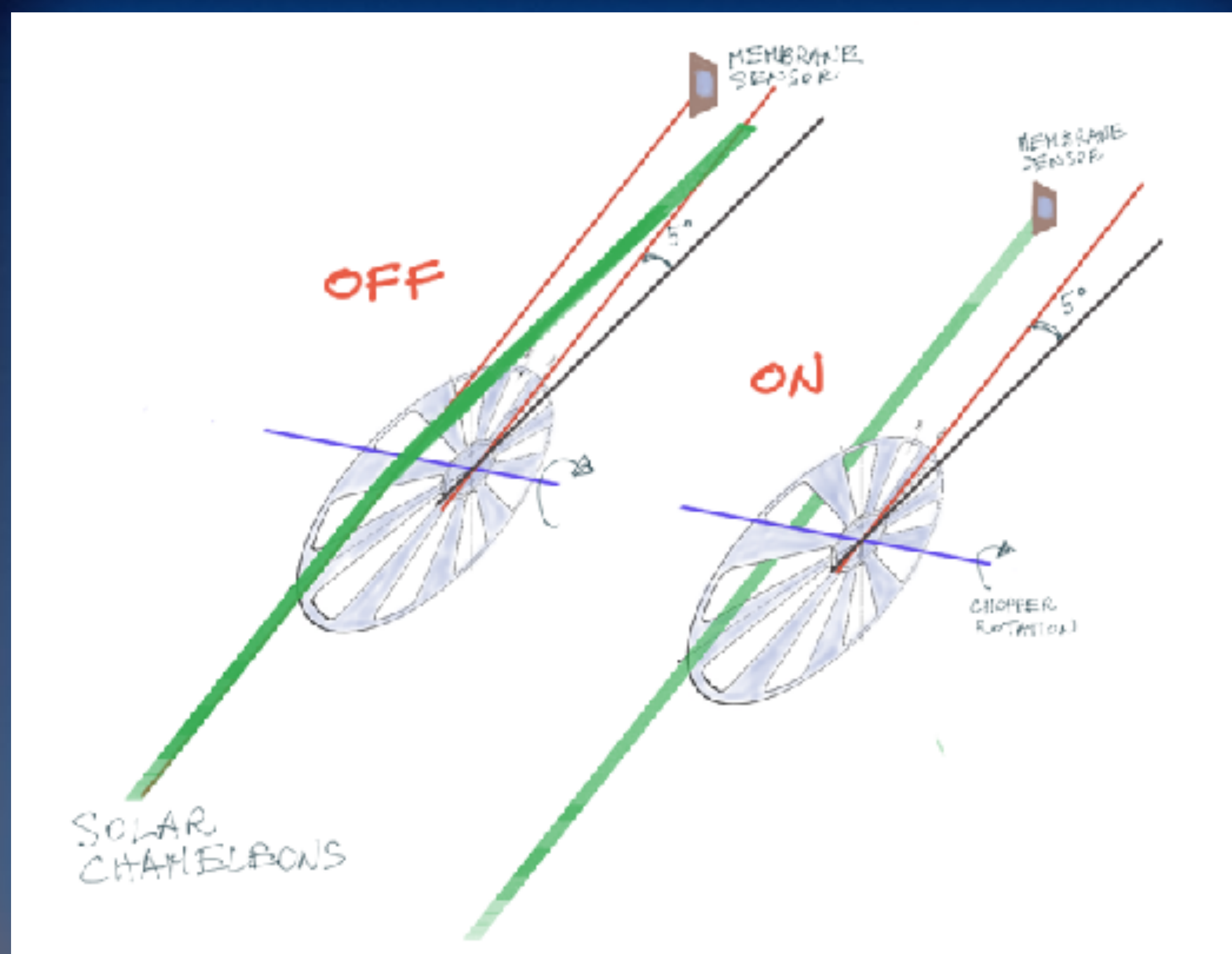
Chameleon chopper

KWISP on the CAST sunrise side



The Chameleon chopper

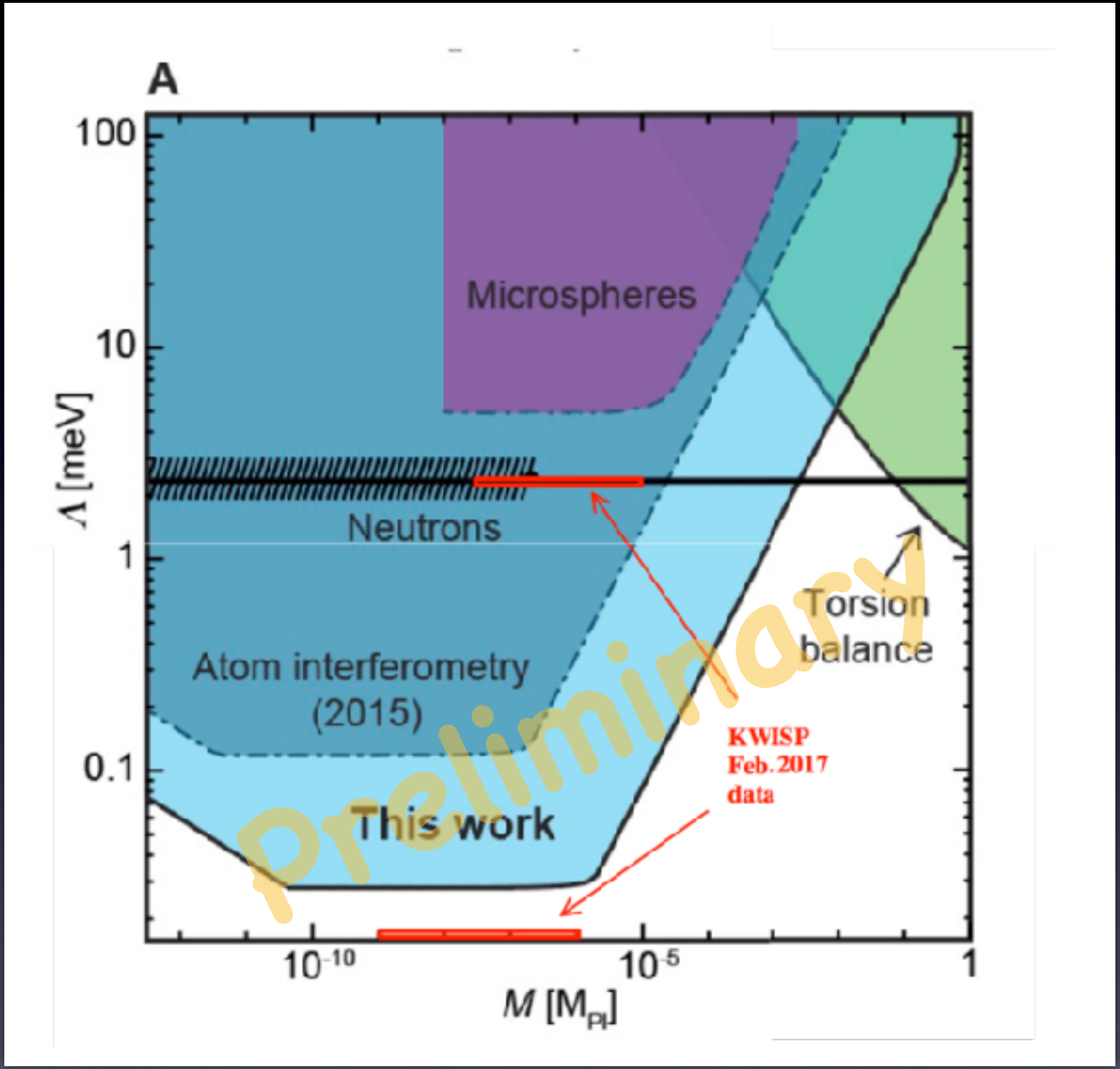
- Why does one need a chopper?
  - the sensor detects *relative* displacements, thus a *static* displacement is not seen
  - a time dependence must then be introduced in the membrane excitation
- Modulating the amplitude of something you cannot even see… the Chamelon chopper!
  - rests on the principle of grazing-angle reflection of Chameleons (see http://arxiv.org/abs/1201.0079)
  - **key element: no detection is possible without**



Log of KWISP solar tracking runs

- **First runs ever with force sensor looking for solar chameleons**
- April 2016
  - pioneering sun-tracking with KWISP 1.0 (michelson interferometry)
  - DAQ acquires interferometer signal and chopper trigger signal
- December 2017
  - sun-tracking with KWISP 1.5 (interferometry with homodyne detection)
  - a calibration signal is briefly injected at the beginning of each time record to obtain on-line calibration
  - data are taken continuously both during and off-tracking
- February 2017
  - sun-tracking with KWISP 1.5 (interferometry with homodyne detection, upgraded DAQ and electronics)

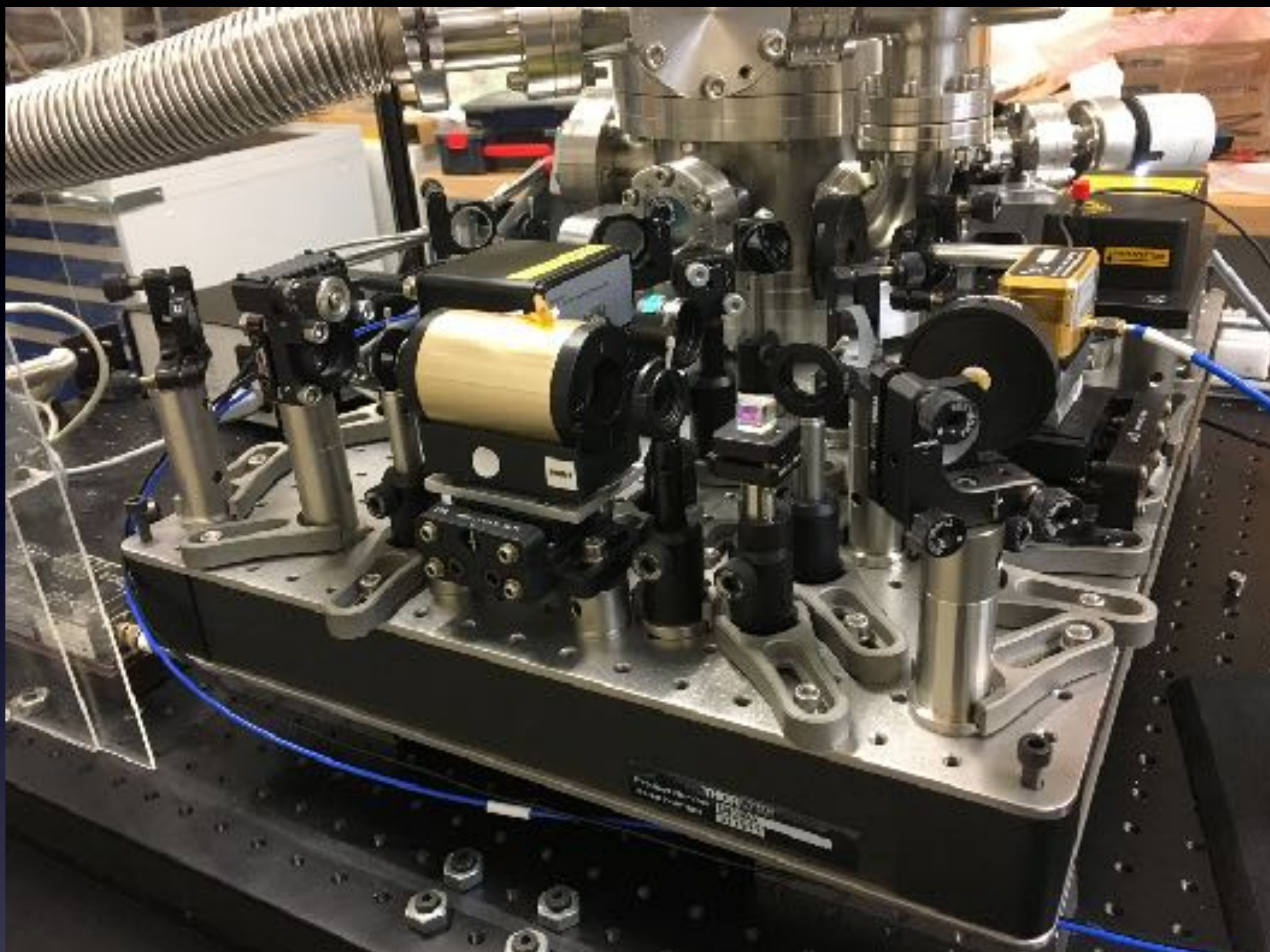
KWISP coverage of chameleon potential parameters

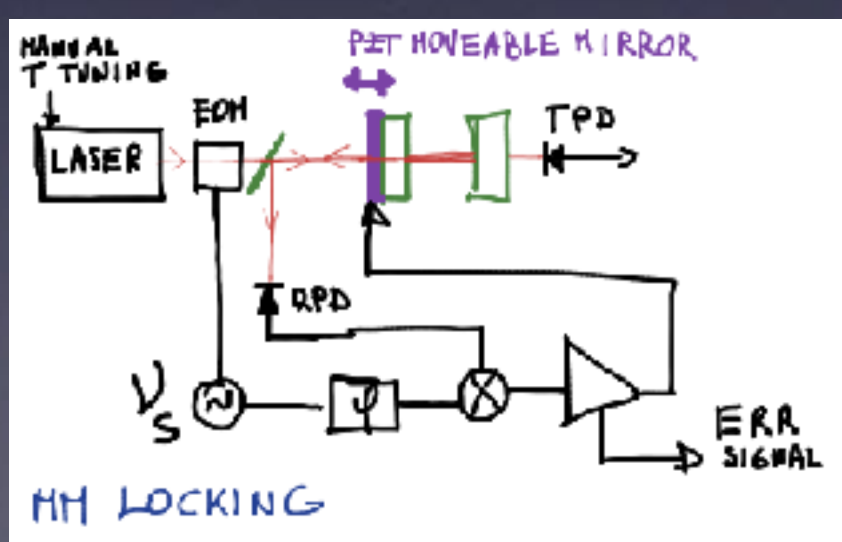


- <u>1.5 sensor</u>: single-pass membrane interferometer with **homodyne detection**
- Sensitivity 10^{-12} N/√Hz
- Measuring time 35580 s

Experimental bounds from KWISP sun-tracking data of Feb. 2017 in the **Λ-M = βm⁻¹** plane (plot taken from https://arxiv.org/abs/1612.05171)

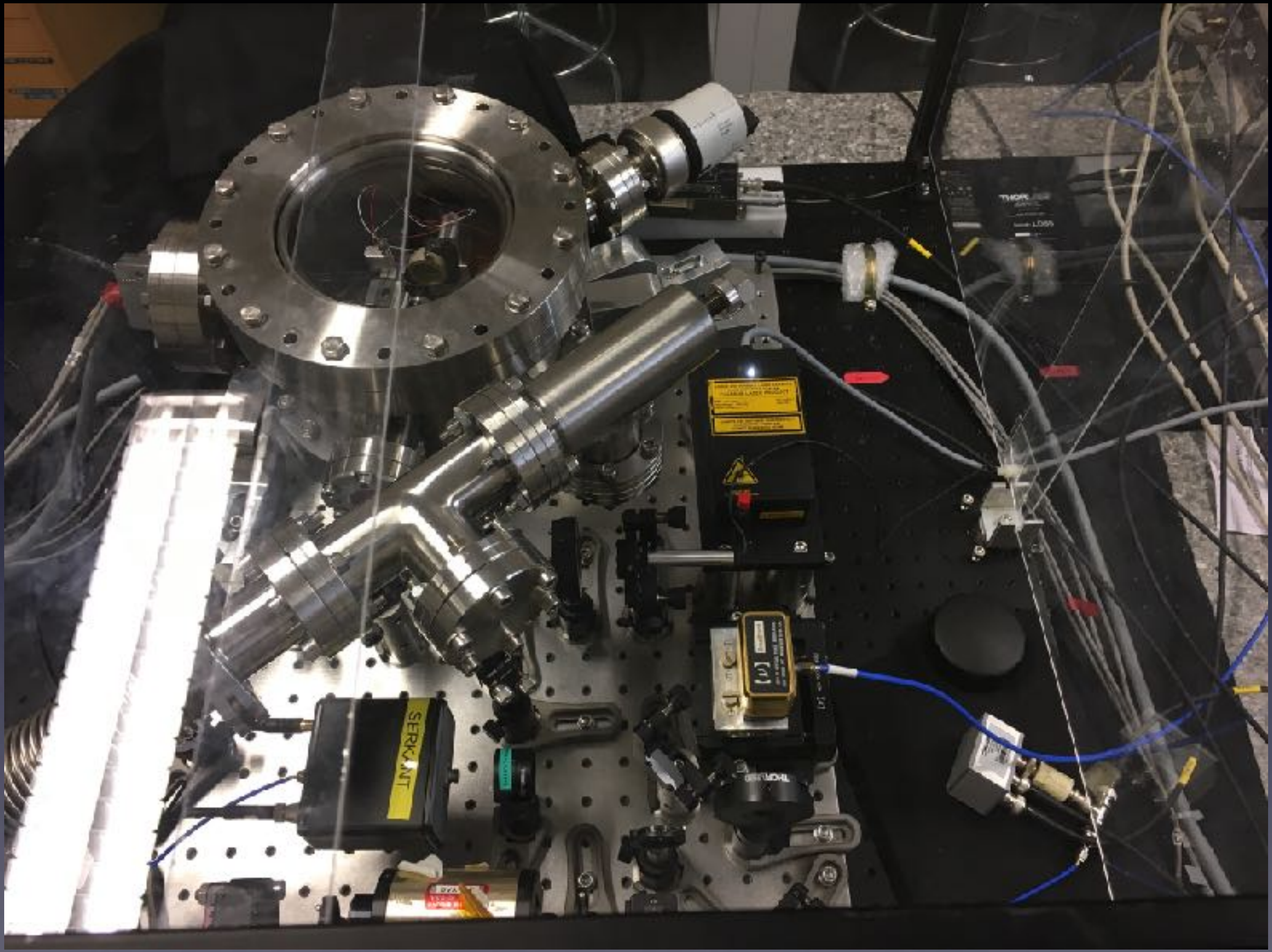
KWISP 2.0 sensor



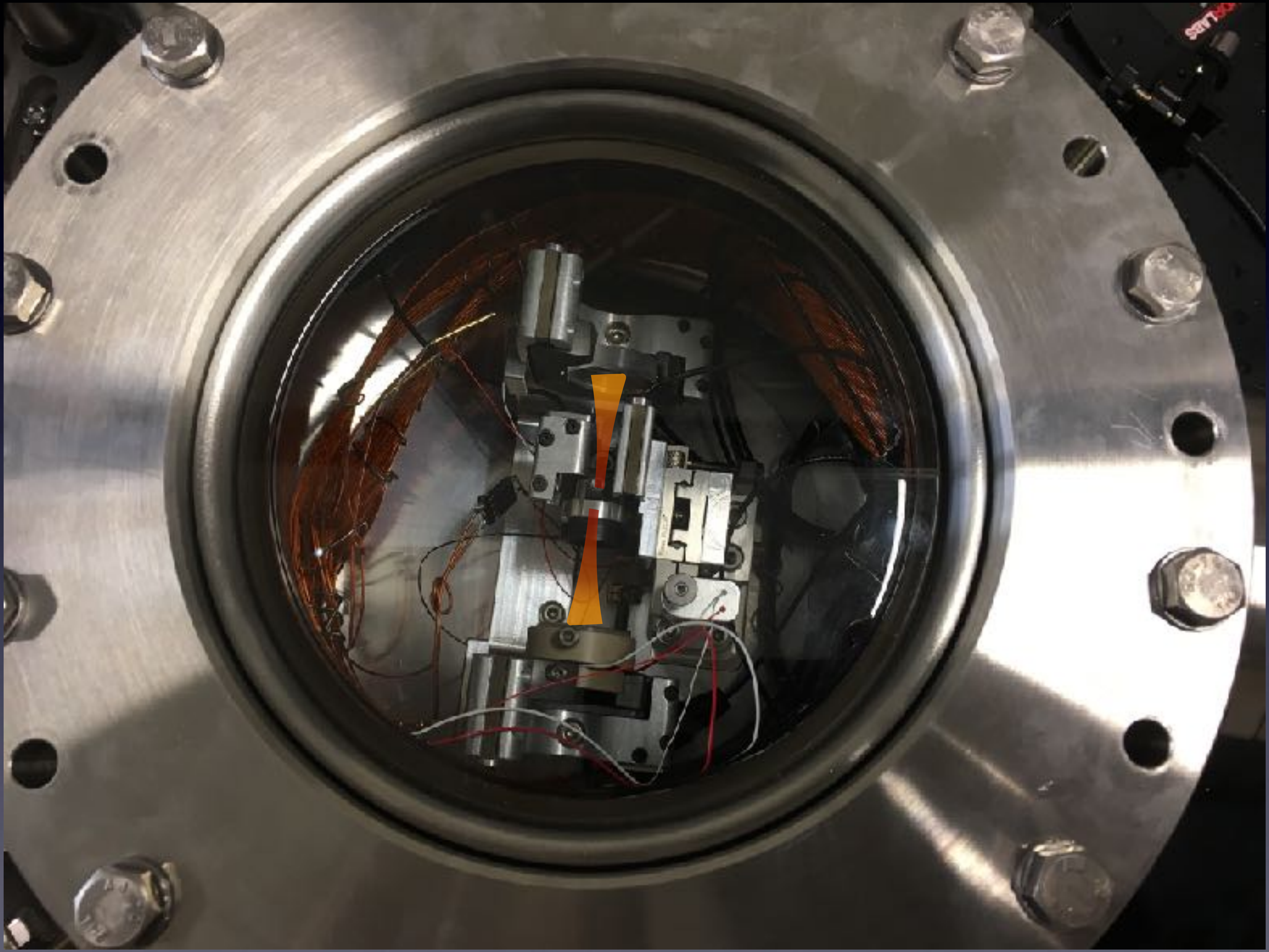


- 1064 nm laser, Fabry-Perot cavity with F~10^4
- PDH frequency-lock with cavity control
- monolithic optical bench
- expected thermally limited sensitivity (10^{-15} N/√Hz at 300 K)
- Status
  - interferometer locked with and without membrane
  - perfomance degraded by laser not meeting specs
  - laser sent back to company for checking

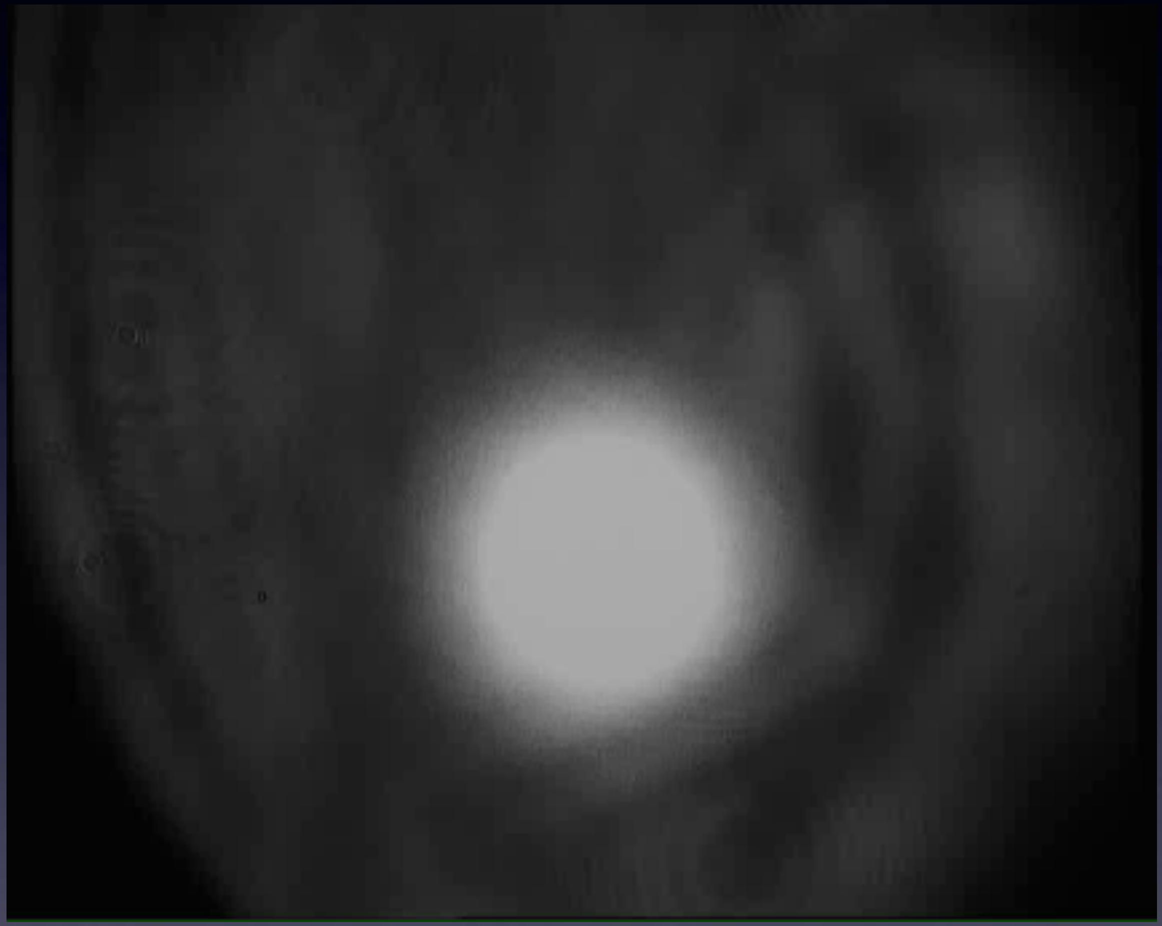
KWISP monolithic optical bench



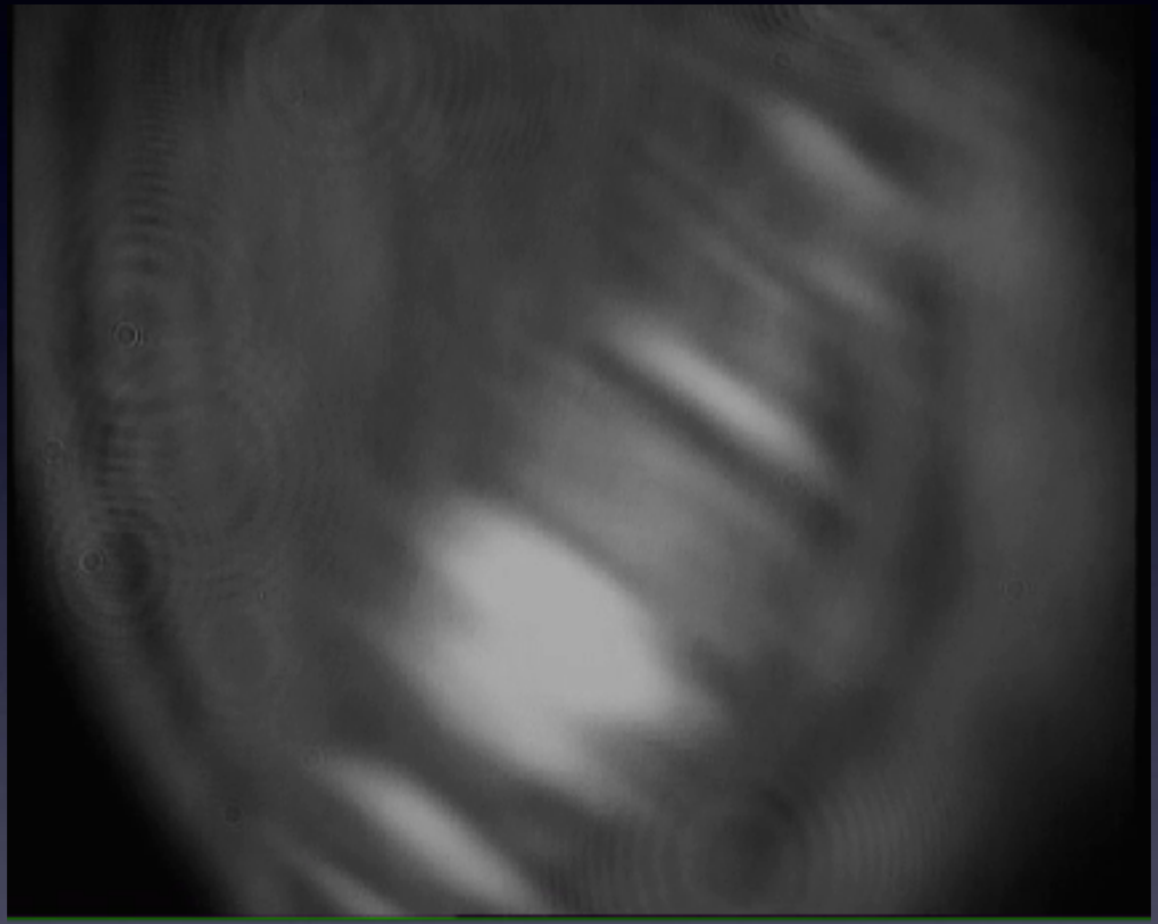
KWISP F-P cavity with membrane



KWISP cavity lock



TEM00 mode, no membrane



Mode mixture with membrane (TEM00 + h.o.m.)

KWISP sensitivity evolution

Data Acq. Run	Displ. sensitivity [m/√Hz]	Force sensitivity [N/√Hz]	Step impr. factor	Thermal limit [N/√Hz]	Factor above thermal	KWISP version	Upgrade
Apr-16	6.00E-09	9.60E-08	1	2.50E-15	3.84E+07	1.0	Initial version
Dec-16	1.00E-11	1.60E-10	600	2.50E-15	6.40E+04	1.5	Homodyne detection
Feb-17	1.20E-13	1.92E-12	83	2.50E-15	7.68E+02	1.5	Updated DAQ
Jun-17		2.50E-15	768	2.50E-15	1.00E+00	2.0	F-P - finesse ~5E+4

Beyond: *a*KWISP

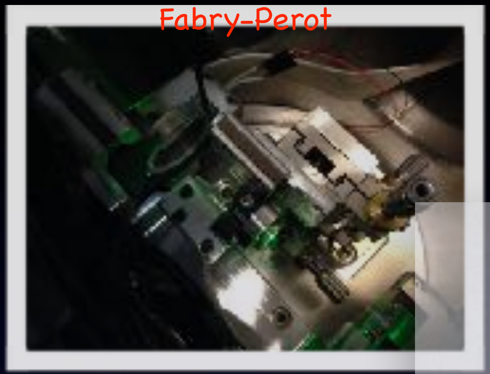
Idea and motivations

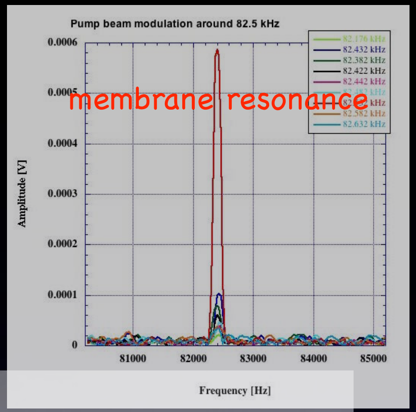
- **Short distance interactions (SDI)** give access to
  - extra dimensions
  - chameleons
  - scalar Dark Matter
  - dilatons
  - **axions**
  - …

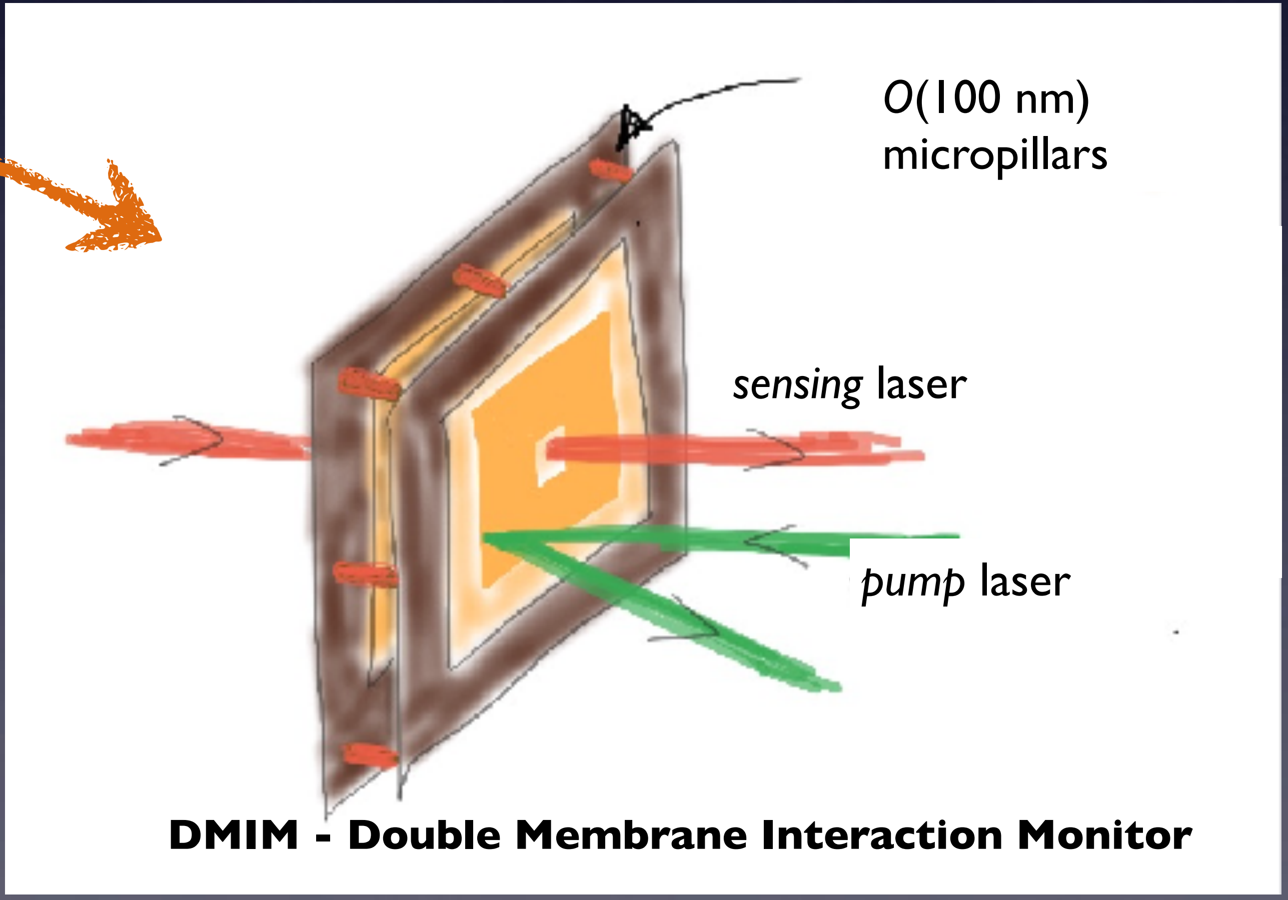
  Basic experimental technique in SDI:
    - **two masses: “source” mass and“sensing” mass**
    - **excite the “source” ⇒ “sensing” mass gives signal *f*(**separation distance**)**
- **We present *a*KWISP, a device able to investigate SDI at O(100 nm) or less separation distances**
  - start from a membrane-based opto-mechanical force sensor
    - KWISP: used at CAST to search for solar Chameleons via their “radiation pressure”
    - **extreme sensitivity comes from the combined quality factors of two resonators**
  - go one step further for ***advanced*-KWISP (aKWISP)**
    - two membranes in close proximity
    - excite one with a pump laser, monitor the other with a sensing laser

*a*KWISP in a nutshell

- **Build on the KWISP force sensor core apparatus**
  - membrane-based optomechanical force sensor
  - **sensitivity enhanced by the combined quality factors of two resonators: mechanical (membrane) and optical (FP)**
  - sensitive to extremely tiny forces and sub-nuclear size displacements
- Introduce the **double-membrane device concept**
  - two membranes separated by *O*(100 nm)-size micropillars acting as **sensing** and **source** masses
  - different Q's and resonant frequencies
- **Implement advanced technologies to achieve the ultimate sensitivity**
  - homodyne detection
  - membrane optimisation
  - cryogenic cooling
- **Study Short Range Interactions**

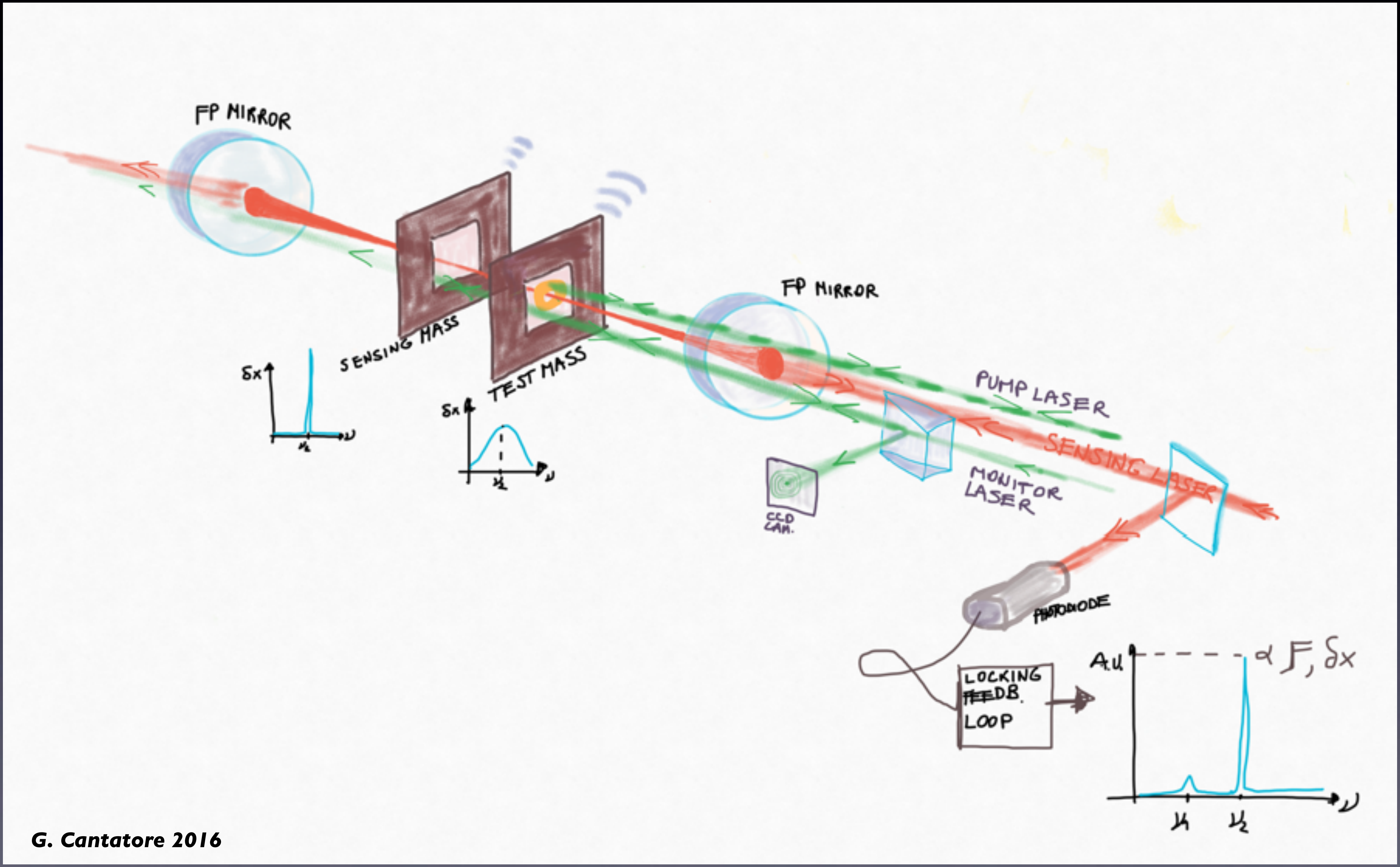






Univ. and INFN Trieste, Univ. of Camerino and INFN Perugia
Univ. of Freiburg, TU Darmstadt, CAPP-IBS (Korea), CERN , Univ. of Patras

*a*KWISP principle schematic



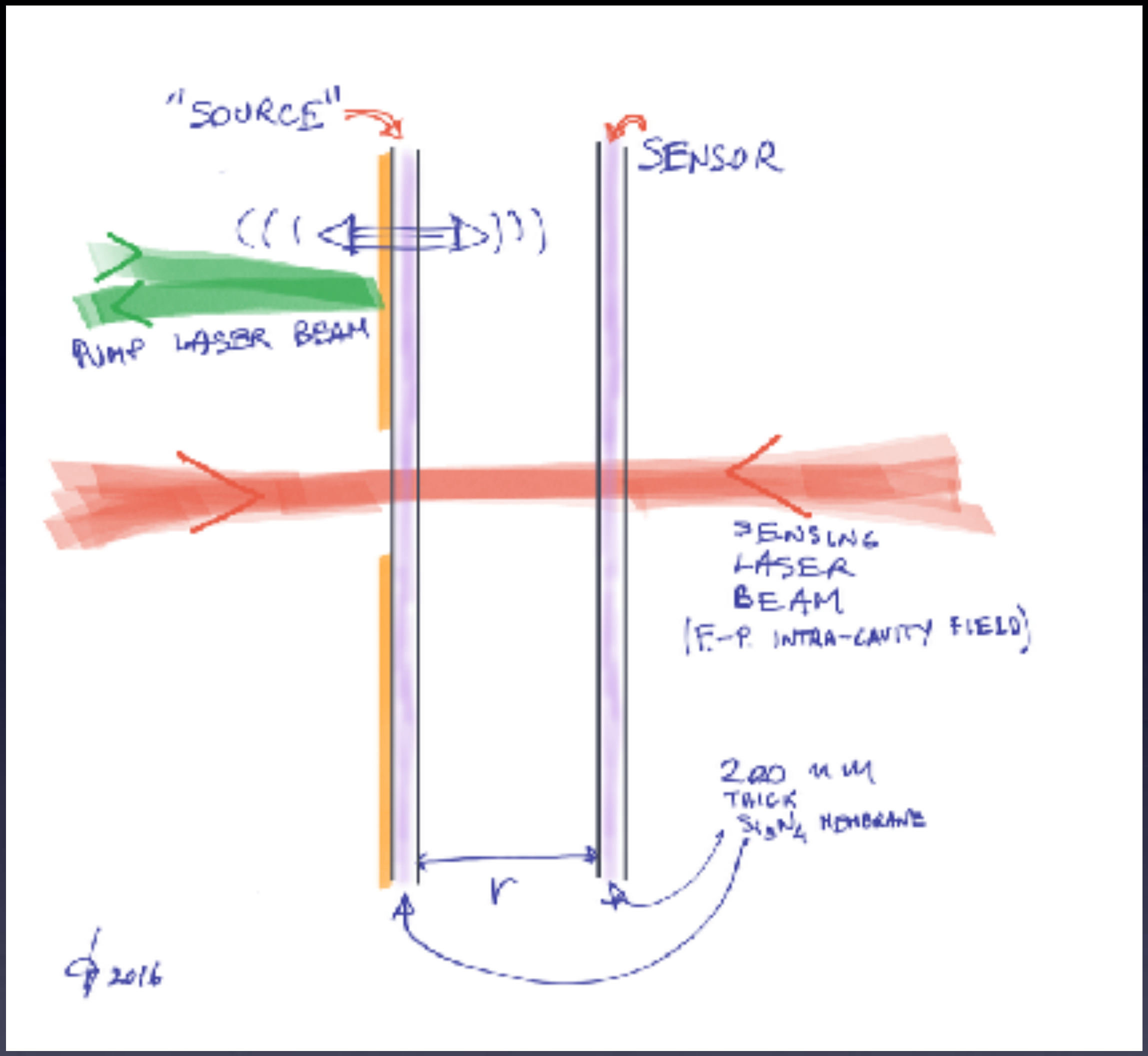
Key *a*KWISP technologies

- DMIM (Double Membrane Interaction Monitor)
- Fabry-Perot resonator
- pump beam calibration
- homodyne detection
- cryogenic cooling
- membrane coating and customisation

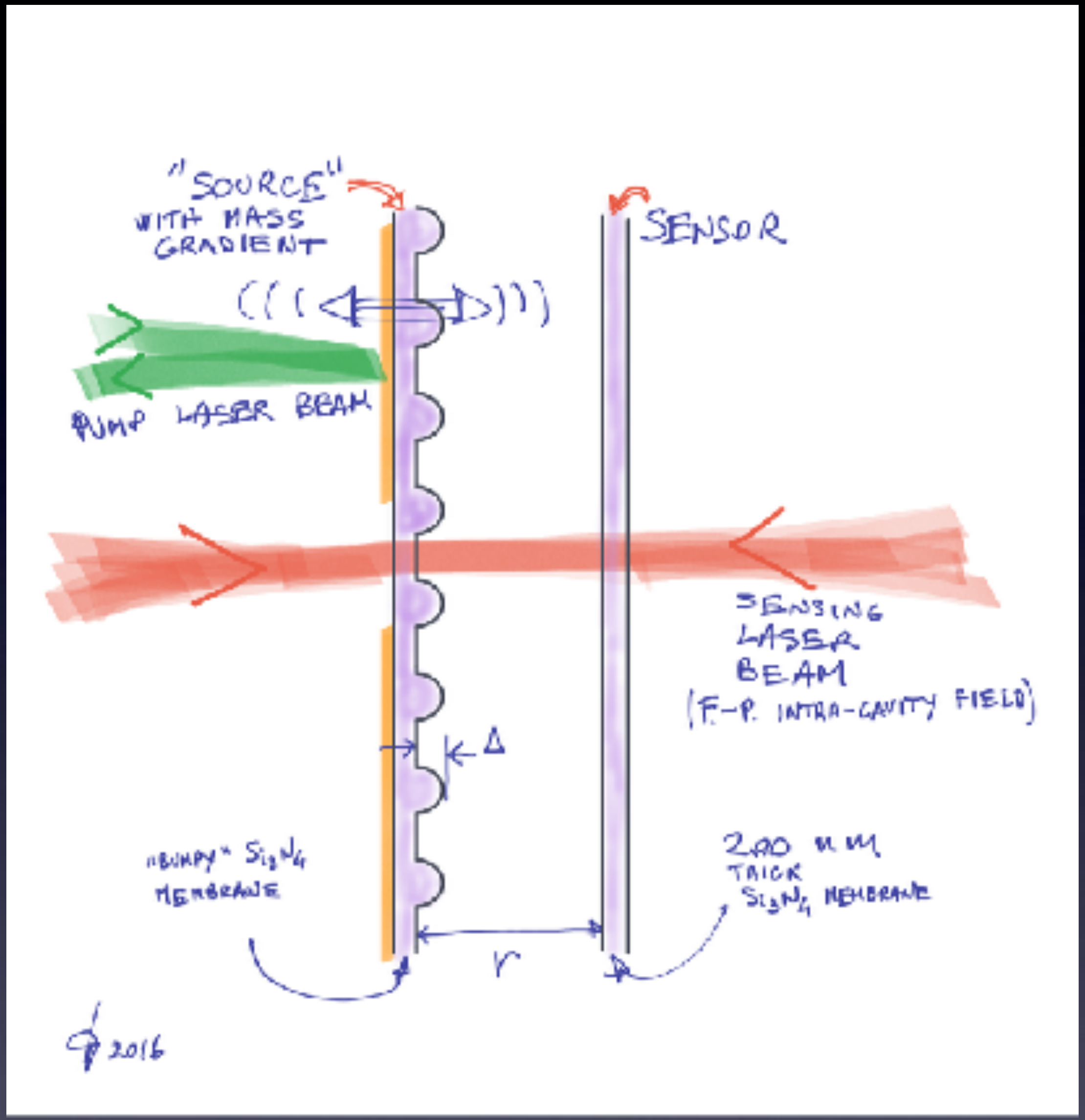
A scenario for *a*KWISP

- The ATLAS experiment at LHC was able recently to explore the compactification of extra dimensions at short distance scales stopping at 11 μm (arXiv:1604.07773 and CERN thesis at https://cds.cern.ch/record/2194414?ln=en)
- Other experiments probe Yukawa-type forces down to 10 μm ⇒ 1 μm (see for example A. Geraci et al., PRD, D78(2), 022002 (2008))
- aKWISP could probe distance scales of O(100 nm) or less reaching atto-N or even zepto-N sensitivities ⇒ unexplored regions in the parameter space of Yukawa-type interactions with access to chameleons, dilatons, scalar DM, …
- Recent suggestions:
  - Y. Semertzidis: introduce a mass gradient to activate axion-mediated short range interactions
  - F. Wilczek: go down to 10 nm separation and investigate the Casimir effect

Sensing axion-mediated forces



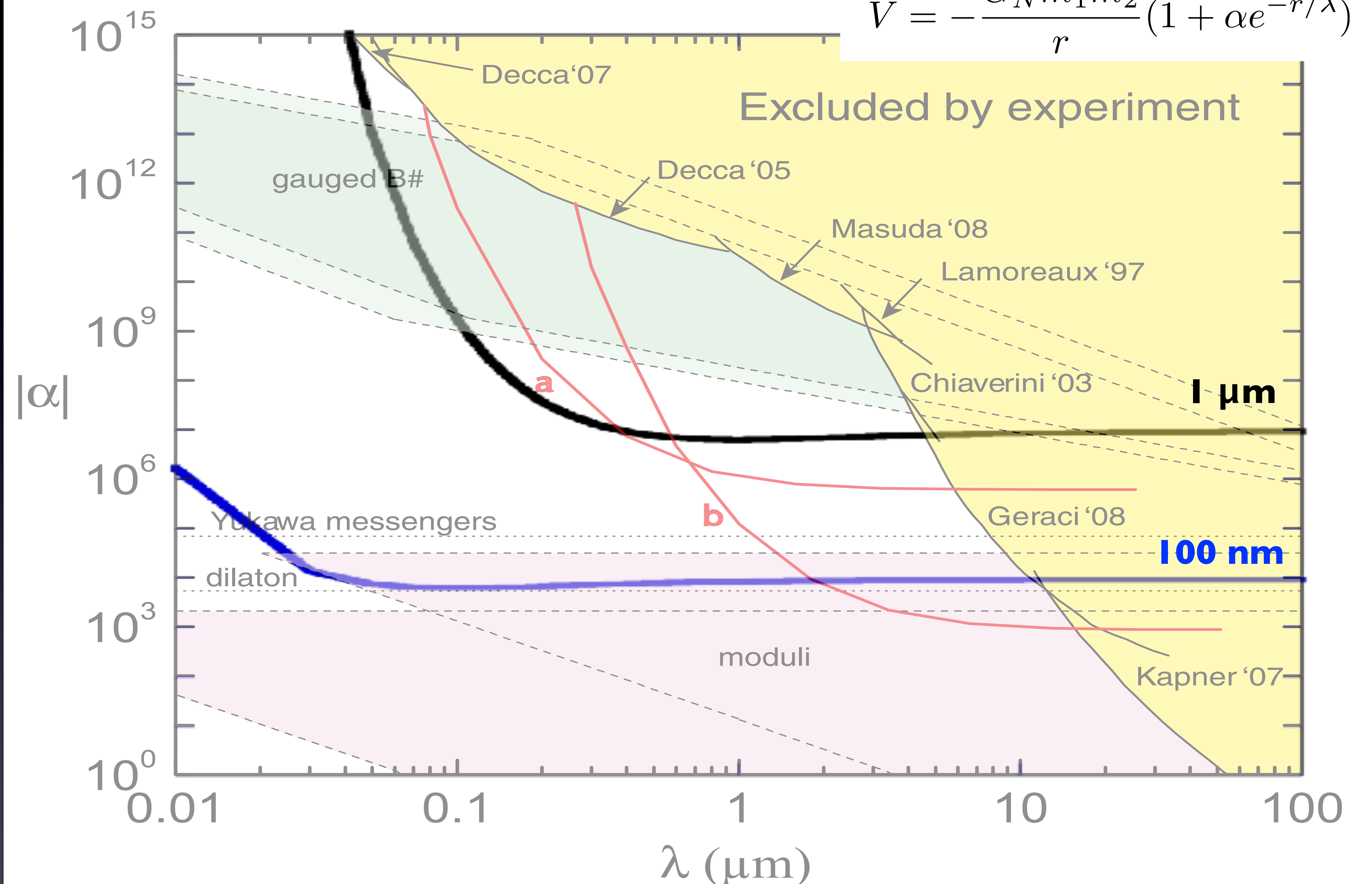
no mass gradient ⇒nucleon coupling



mass gradient ⇒ spin coupling

*a*KWISP physics reach for Yukawa-type interactions

$$V = -\frac{G_N m_1 m_2}{r}(1 + \alpha e^{-r/\lambda})$$



Exclusion plot taken from; A. Geraci et al., Physical Review Letters, 105(10), 101101 (2010)

Projected *a*KWISP detection @ 3 mK with 10^5 s integration time = 10^{-20} N

- black curve: 1 micron separation distance
- blue curve: 100 nm separation distance

Conclusions

- CAST completed its solar axion program again setting the reference over a wide axion mass range
- CAST has launched a new physics program centered on Dark Matter (relic axions with CAPP) and Dark Energy (chameleons with InGrid and KWISP)
- Building on our expertise on membrane force sensors, we present ***a*KWISP**: a novel device to investigate short range interactions at separation distances *O*(100 nm) or less
- ***a*KWISP** has the potential to venture deeply into uncharted territory searching for axions and other exotics


Thank you!
We have great ideas !!
… mo' ce tocca lavorà!
GC
MK